

General Disclaimer

One or more of the Following Statements may affect this Document

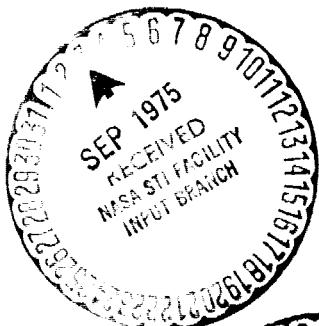
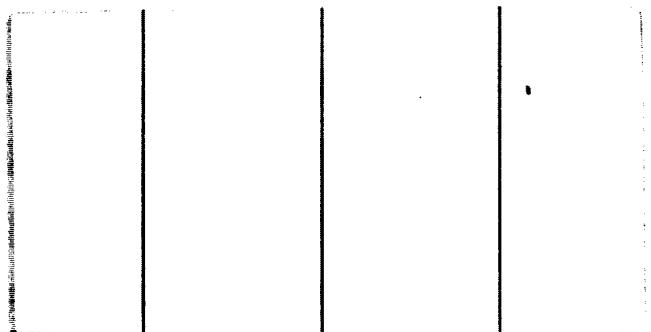
- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.
- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.
- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.
- This document is paginated as submitted by the original source.
- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

DRA

(NASA-CF-145850) A COMPARATIVE STUDY OF
SIMULTANEOUSLY MEASURED He⁽⁺⁺⁾ FLUXES IN THE
SOLAR WIND AND IN THE MAGNETOSPHERE
UTILIZING IMP-1 AND 1971-089A SATELLITE DATA
Final Report (Lockheed Missiles and Space

N76-14008

Unclassified
G3/92 15016



LOCKHEED

MISSILES & SPACE COMPANY, INC. • SUNNYVALE, CALIFORNIA

A SUBSIDIARY OF LOCKHEED AIRCRAFT CORPORATION

LMSC/D460620

22 August 1975

FINAL REPORT

CONTRACT NASW 2554

A Correlative Study of Simultaneously
Measured He⁺⁺ Fluxes in the Solar
Wind and in the Magnetosphere Utilizing
IMP-I and 1971-089A Satellite Data

Prepared by:

Dr. Edward G. Shelley
Space Sciences Laboratory
Lockheed Palo Alto Research Laboratory
Lockheed Missiles & Space Company, Inc.
3251 Hanover Street
Palo Alto, California 94304

TABLE OF CONTENTS

	<u>Page</u>
INTRODUCTION.....	1
ACCOMPLISHMENTS.....	3
SUMMARY AND CONCLUSIONS.....	15
REFERENCES.....	16
APPENDIX A, "DAYSIDE CONVECTION ELECTRIC FIELD DEDUCED FROM ION MEASUREMENTS IN THE LOW-ALTITUDE CUSP," by E. G. Shelley, R. D. Sharp, and R. G. Johnson (Abstract).....	A-1
APPENDIX B, "SIMULTANEOUS He^{++} AND H^+ OBSERVATIONS IN THE SOLAR WIND AND THE LOW-ALTITUDE DAY- SIDE CUSP," by E. G. Shelley and W. C. Feldman (Abstract).....	B-1
APPENDIX C, " He^{++} AND H^+ FLUX MEASUREMENTS IN THE DAYSIDE CUSP: ESTIMATES OF CONVECTION ELECTRIC FIELD," by E. G. Shelley, R. D. Sharp, and R. G. Johnson.....	C-1

Final Report - Contract NASW 2554

A CORRELATIVE STUDY OF SIMULTANEOUSLY MEASURED He^{++} FLUXES IN THE SOLAR WIND AND IN THE MAGNETOSPHERE UTILIZING IMP-I AND 1971-089A SATELLITE DATA

INTRODUCTION

This is the final report on a correlative study of simultaneously measured He^{++} fluxes in the solar wind and in the magnetosphere using data from the Los Alamos Scientific Laboratory plasma spectrometer on the Imp I satellite in the solar wind and the Lockheed Palo Alto Research Laboratory energetic ion mass spectrometer on the low altitude polar orbiting satellite 1971-89A. The principal results of this program were obtained from a detailed comparison of the He^{++} energy spectrums measured simultaneously in the solar wind and in the low altitude dayside polar cusp on March 7, 1972. The energy-per-unit-charge range of the energetic ion mass spectrometer on board the polar-orbiting satellite was 700 eV to 12 keV. Within this range there was a clear maximum in the He^{++} energy spectrum at approximately 1.5 keV/nucleon. There was not a clearly-defined maximum in the H^+ spectrum, but the data were consistent with a peak between 0.7 and 1.0 keV/nucleon. Both spectra could be reasonably well fit with a convecting Maxwellian plus a high-energy tail; however, the mean velocity for the He^{++} distribution was significantly greater than that for the H^+ distribution. The simultaneous solar wind measurements showed the mean velocities for both ion species to be approximately 600 km/sec. The discrepancies between the relative velocity distributions in the low-altitude cusp and those in the solar wind are consistent with a potential difference of approximately 1.4 kV along their flow direction between the two points of observation.

Other results of this program include the development of a new technique for deducing the day-side convection electric field from ion measurements in the low altitude polar cusp.

Four publications have resulted in whole or in part from the research efforts performed under this contract. They are:

1. Dayside Convection Electric Field Deduced From Ion Measurements In The Low Altitude Cusp, E. G. Shelley, R. D. Sharp, R. G. Johnson, Trans. Am. Geophys. U., EOS, 55, 1175, 1974
2. Simultaneous He⁺⁺ and H⁺ observations in the Solar Wind and the low altitude dayside cusp, E. G. Shelley and W. C. Feldman, Trans. Am. Geophys. U., EOS, 56, 431, 1975
3. He⁺⁺ and H⁺ Flux Measurements In The Dayside Cusp: Estimates Of Convection Electric Field, E. G. Shelley, R. D. Sharp, R. G. Johnson, submitted to The Journal of Geophys. Res. (1975)
4. Observations of He⁺⁺ and H⁺ spectral changes between the solar wind and the low altitude dayside cusp, E. G. Shelley and W. C. Feldman in preparation - to be submitted to The Journal of Geophys. Res.

Abstracts of the first two of the above listed publications and a preprint of the third are included in the Appendices.

ACCOMPLISHMENTS

The principle objective of this program was to utilize a unique set of simultaneous measurements of the He⁺⁺ component of the solar wind and the magnetospheric plasma to obtain added leverage on the unresolved problems of plasma access to, and transport and acceleration processes within, the magnetosphere. The Lockheed energetic ion mass spectrometer experiments have provided the only satellite data on the composition of the magnetospheric plasma in the keV range. The spectrometer on the satellite 1971-89A covered the mass per unit charge range between 1 and 32 AMU and the energy per unit charge range from 700 eV to 12 keV. The initial results from the experiment have been reported by Shelley et al (1972, 1974), Johnson et al (1974), and Sharp et al (1974).

During the spring of 1972 the Imp I satellite orbit was such as to provide extensive coverage in the solar wind. Although, it is not a mass spectrometer, the Los Alamos plasma spectrometer on Imp I has sufficient energy range and resolution to separate the He⁺⁺ flux from the H⁺ flux under most solar wind conditions and to determine the temperature and density of both species.

The best example of simultaneously acquired data of high quality when there was a substantial He⁺⁺ component to the plasmas measured in both experiments occurred on March 7, 1972 and the bulk of the effort under this program was devoted to the analysis of that data. One of the significant accomplishments in the course of this analysis was the development of a sophisticated least-squares fitting code to accurately separate the He⁺⁺ component in the mass spectra from the penetrating background and interference from neighboring masses (principally H⁺). Due to the finite mass resolution of the spectrometers, the "tail" of the H⁺ peak has an amplitude in the vicinity of the He⁺⁺ peak as great as a few percent of the H⁺ peak. Thus, when the He⁺⁺ flux is only a few percent of the H⁺ flux, one must establish the detailed "line shapes" of the response of the spectrometers to the various ion species and effectively "strip out" the effects of interference. This is best done by varying the "strengths" of the various ion species and searching for a minimum in χ^2 .

The code which has been developed utilizes the known response functions for the various ion species to establish the relative strengths and their statistical significance. An example of a fit to some of the flight data is shown in Figures 1 and 2. Figure 1 shows the raw data together with the count rates expected for a combination of $M/Q = 1, 2$ and 16 plus a uniform background. Figure 2 shows the individual mass components together with the data. In the application of the code to data with either poor counting statistics or very good statistics, we discovered some significant biasing. For that reason, it was necessary to make certain adjustments to the code. In the case of poor statistics (i.e., counting statistics of the order of 10 and less) we found that the normal definition of the standard deviation as $\sigma_N = \sqrt{N}$ led to an unacceptably high weighting of the low count rate points in the spectrum. This can be understood if one considers low level counting of a source which is constant except for statistical effects. Consider a source which produces a mean count of 9. Approximately 15% of the time the count will be less than $(9 - \sqrt{9}) = 6$. Likewise, approximately 15% of the time the count will be greater than $(9 + \sqrt{9}) = 12$. If we use the normal weighting of $\frac{1}{\sigma^2}$ for each measurement we find that the low count of 6 has been given twice the weight of the high count of 12, thus biasing the fit toward lower counts when in fact the difference resulted only from random effects in an otherwise constant counting rate. This effect becomes unimportant when $\sigma/N \ll 1$. We therefore incorporated into the code the capability of limiting the weighing on the low count points in the mass spectrum and verified that the bias is reduced to a statistically acceptable level. In the case of very "good" statistics, we found that for $\sigma/N \lesssim 0.05$ the uncertainties in the shape of the spectral peaks was comparable to or greater than the purely statistical errors. In this case too much weight is placed on the high count points if $\sigma = \sqrt{N}$ is used. This problem was solved by not permitting σ/N to be reduced below the estimated peak shape uncertainty of 0.05.

As a first step in the analysis of the mass spectrometer data we utilized the above described code to study the energy spectrums of the He^{++} and H^+ ions measured during a traversal of the dayside polar cusp at about 0530 UT on March 7, 1972 for a comparison with the simultaneously measured spectrums

ORIGINAL PAGE IS
OF POOR QUALITY.

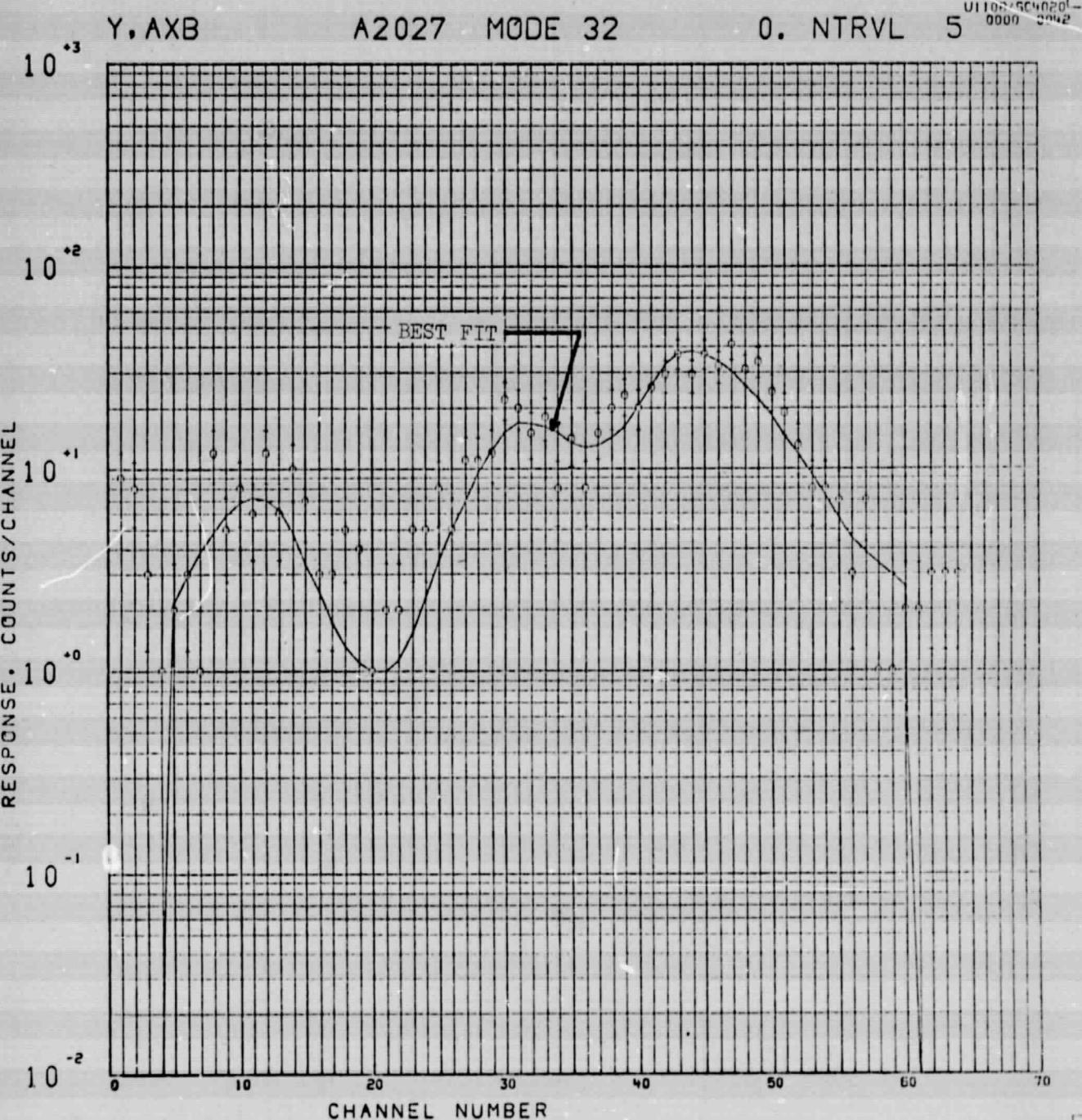


Figure 1. The open circles with statistical error bars are data taken near the dayside cusp on March 7, 1972. The data were summed over 5 mass spectrum sweeps. The solid curve is the "best fit" to the data assuming a combination of $M/Q = 1$, $M/Q = 2$, $M/Q = 16$, and a uniform background. See Figure 2 for separate components.

Y.AXD

A2027 MODE 32

0. NTRVL 5

00000 0044

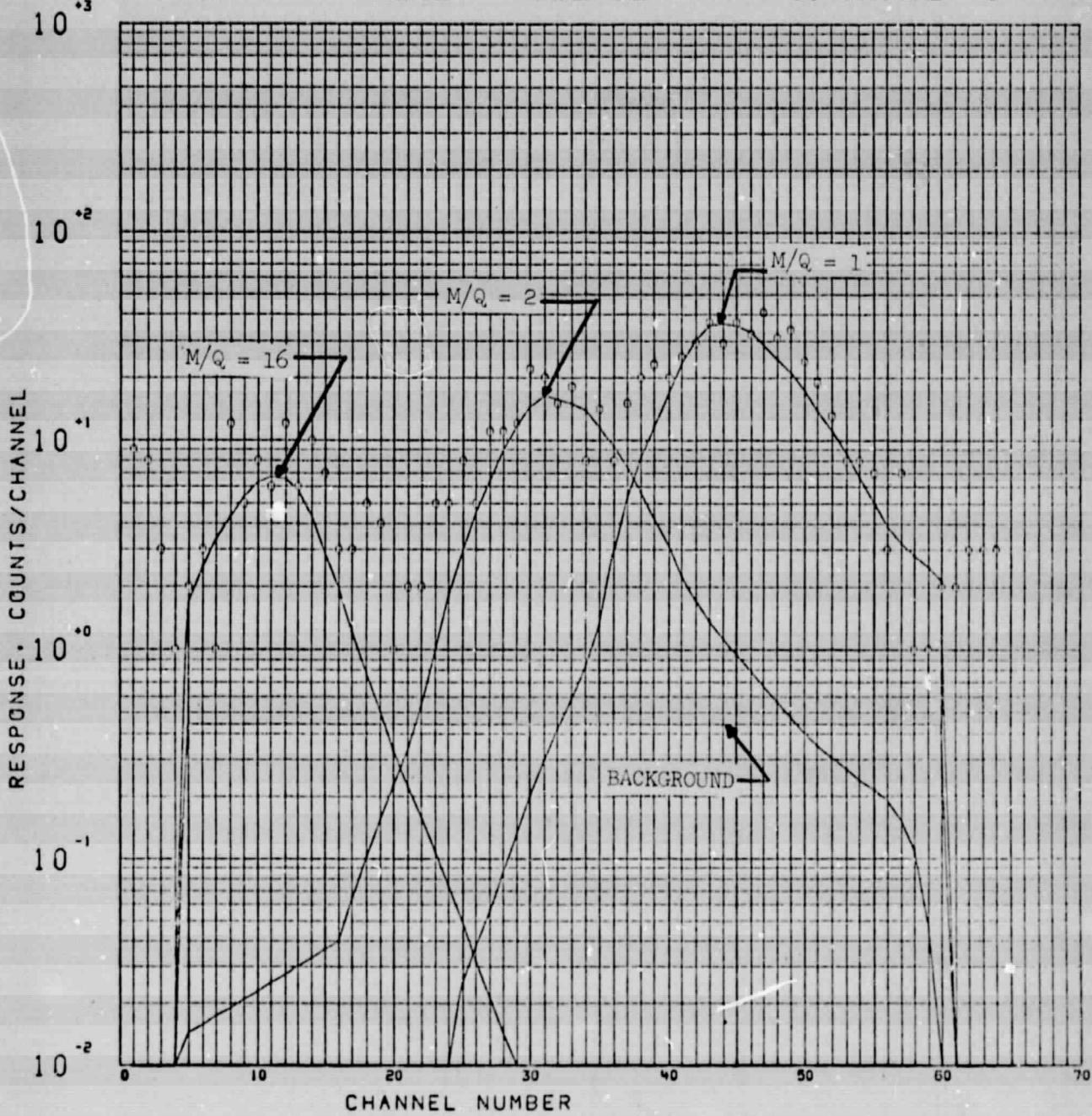


Figure 2. Same as Figure 1, but with the independent mass components and the background shown separately at their relative strengths.

in the solar wind. Imp 6 was at a geocentric distance of about 31 RE at this time near the sun-earth line while the 1971-89A experiment was sampling precipitating cusp particles at an altitude of about 800 km, a magnetic local time of about 1115 and a pitch angle of about 55°.

Figure 3 shows the solar wind parameters during the period of interest (data provided by W. C. Feldman). The vertical dashed line indicates the time of the polar cusp traversal. At this time the solar wind speed was about 600 km/second, its temperature was between 2 and $4 \times 10^{5\circ}$ K/AMU, the alpha/proton number density ratio was about 5% and the phase space density ratio was about 12%. Figure 4 shows the polar cusp velocity or energy per nucleon spectrums averaged over the entire period of the polar cusp traversal (≈ 74 seconds). This averaging was required to remove the spectral distortions caused by the transit of the ions down the cusp field lines under the influence of the convection electric field (see Appendix C). The effect of this averaging on the flux amplitude is to decrease the peak values by about a factor of 5. One sees in Figure 4 that the He^{++} spectrum exhibits a clear maximum at ≈ 1.5 keV/AMU while the H^+ data is consistent with a peak at about 1 keV/AMU or lower. The solid lines represent fits to a convecting Maxwellian as would be appropriate for solar wind or magnetosheath plasma. The best fit parameters for the He^{++} ions are temperature = $8 \times 10^{6\circ}$ K and velocity = 470 km/second and for the H^+ ions, temperature = $2.6 \times 10^{6\circ}$ K and velocity = 300 km/second. The temperature ratio in the cusp ($T_{\alpha}/T_p = 3.1$) corresponds fairly well to that observed in the solar wind (see Figure 3), but the ratio of the maximums in phase space density in the cusp ($\approx .05$) is significantly lower than the most probable value at this time in the solar wind. The H^+ spectrum could also be fit with a convecting Maxwellian of lower velocity and higher temperature but no reasonable fit can be achieved utilizing the same bulk velocity for the two species. Since the velocity distributions for the two species are approximately equal in the solar wind we attribute the difference to processes acting upon the ions in their traversal through the bow shock and magnetosheath and into the polar cusp. One candidate mechanism that would act differently on the two species is an electrostatic deceleration. Since the He^{++} ions are doubly charged such a mechanism should be twice as

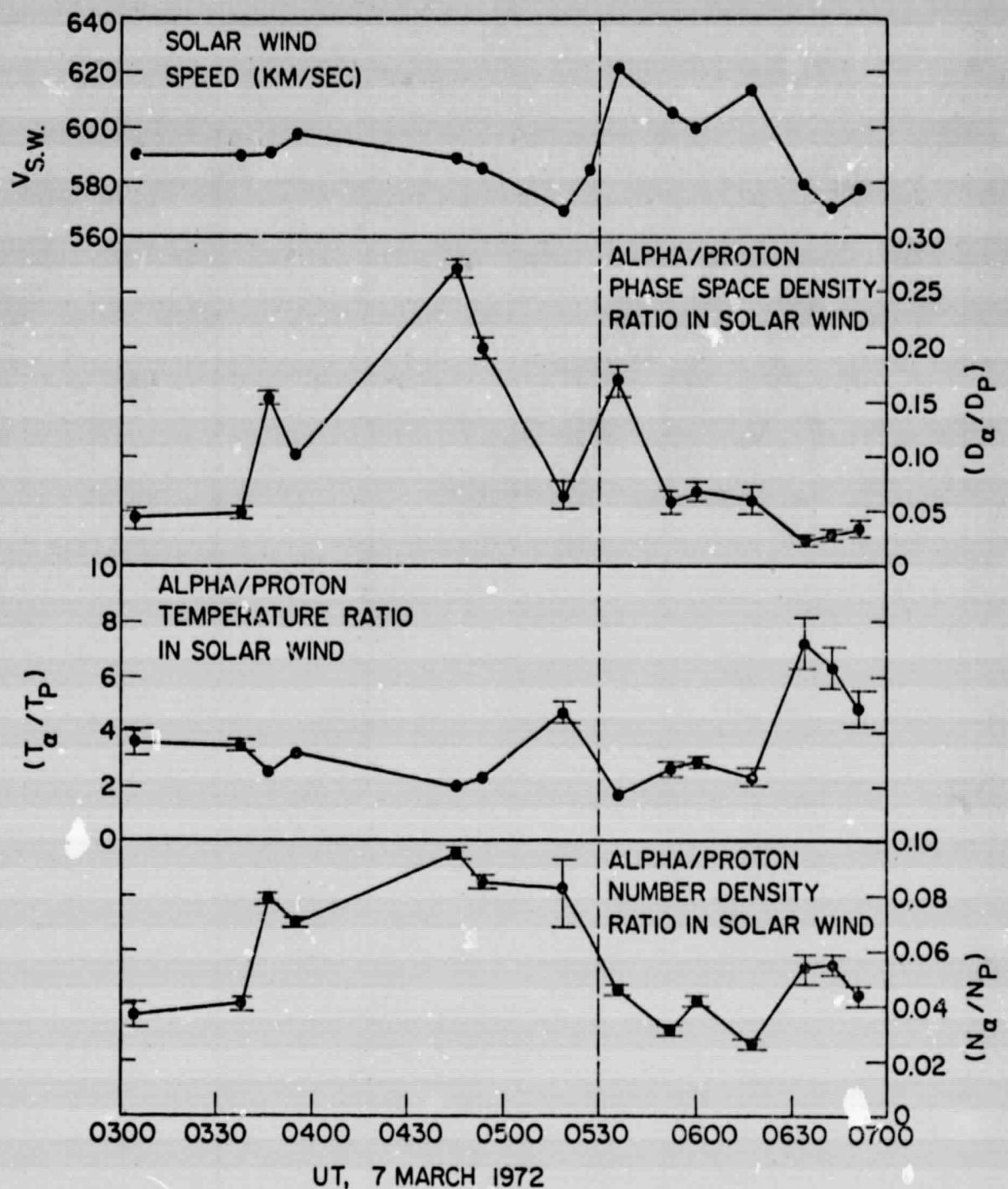


Figure 3. Solar wind parameters measured by the LASL plasma probe on IMP-6. The upper panel is the measured solar wind speed for the H^+ ions. The He^{++} speed differed from this by less than 30 km/sec during the interval covered. The second panel from the top is the ratio of phase space densities in the solar wind for He^{++} and H^+ . The next curve is the He^{++}/H^+ temperature ratios and the bottom curve is the number density ratio. The vertical dashed line indicates the approximate time of the cusp measurements.

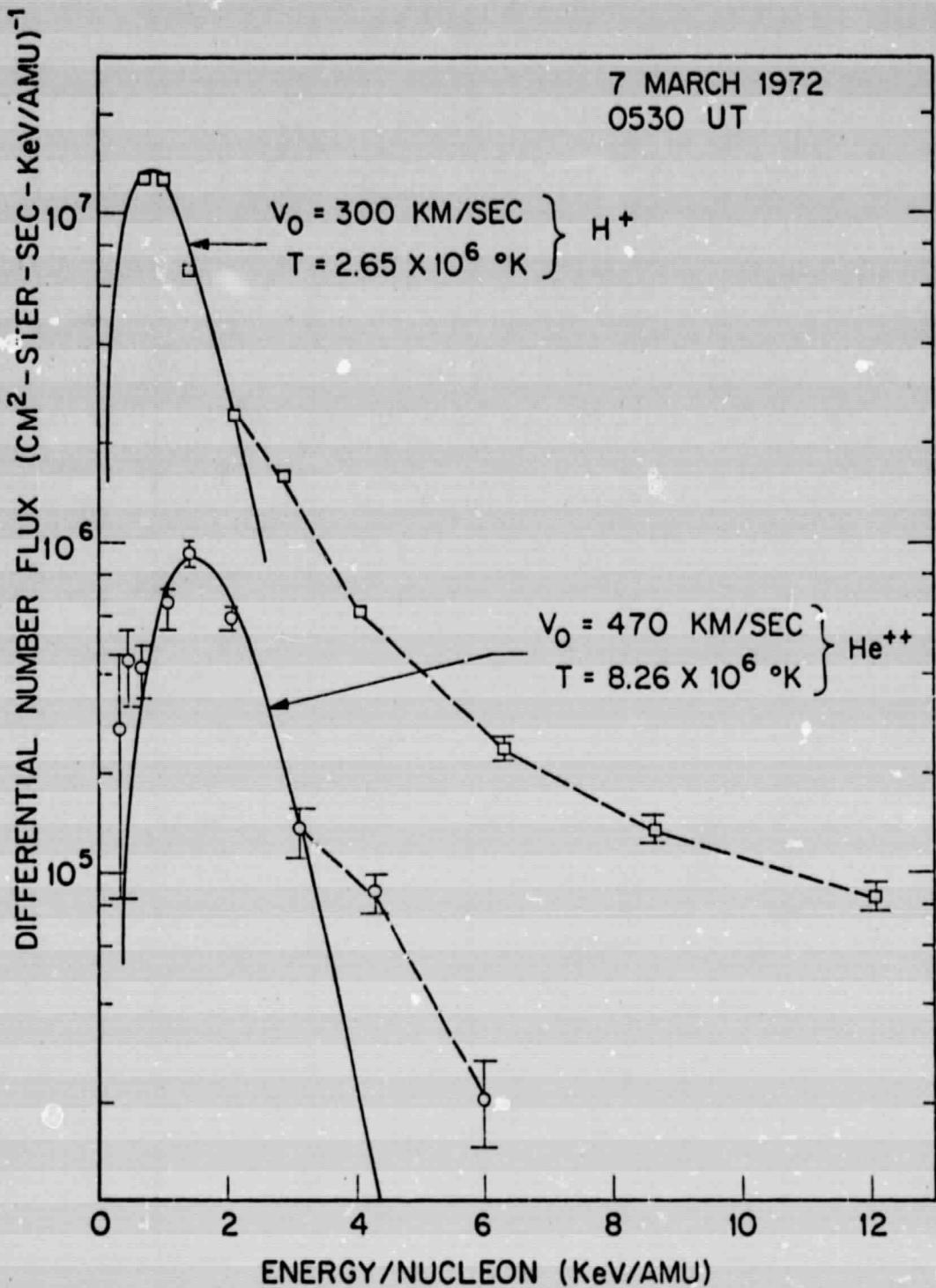


Figure 4. Energy per nucleon differential number flux spectra for He^{++} and H^+ ions averaged over the low-altitude cusp region. Error bars indicate counting statistics only. The solid curves are convecting Maxwellian distributions normalized to the flux maxima for the two species with the flow speeds and temperatures indicated. The dashed lines are only to aid the eye in following the experimental data. Note that the effective flow speed for the He^{++} is significantly greater than for the H^+ .

effective on that constituent as on the protons. On the basis of energy per nucleon, however, the protons are decellerated twice as much as the He^{++} . A best fit to a single convecting Maxwellian for the two ion species allowing for such an electrostatic decelleration is shown in Figure 5. The electrostatic potential which was treated as a free parameter came out to be 1.4 kilovolts. The resultant temperature ($T = 1.3 \times 10^{68} \text{ K/AMU}$), bulk velocity (600 km/sec) and density ratios ($\text{He}^{++}/\text{H}^+ \approx .07$) can be compared to the simultaneous solar wind values in Figure 3. The bulk velocity and density ratio of the cusp ions are in the expected range and the cusp temperature is higher by a factor of 3-6. One, of course, expects heating of the solar wind ions in traversing the bow shock. We see therefore that the data are indeed consistent with the assumed decelleration. Such a process was also suggested by the measurement of Neugebauer (1970) who observed a more rapid slowing of the H^+ than the He^{++} ions in the bow shock prior to their heating to the point where the two species became unresolved.

Depending upon the details of the postulated mechanism there are alternative ways of fitting the spectrums of the two ions species. For example, the spectral shift illustrated in Figure 5 did not conserve phase space density. Since the peak phase space density observed in the cusp is one to two orders of magnitude less than that observed in the solar wind it is not necessary that phase space density be conserved in all the processes acting upon that small fraction of the ions that eventually reach the low altitudes. It is however possible that phase space density is conserved. Figure 6 shows the original cusp spectrums plotted in phase space and Figure 7 shows these spectrums shifted to conform with an assumed electrostatic decelleration of 1.5 keV under the added constraint of conservation of phase space density. We see in Figure 7 that there is less good agreement between the distribution functions of the two ion species than was obtained in Figure 5 and also a less good fit to the assumed thermal distribution functions. The resulting alpha to proton density ratio is about 4% and the temperature ratio, $T_\alpha/T_p \approx 5$. We conclude that although this hypothesis does not result in as good a fit as that leading to Figure 5, it is not clearly excluded. In either case the data are consistent with a process providing equal access to both ion species to the low altitude

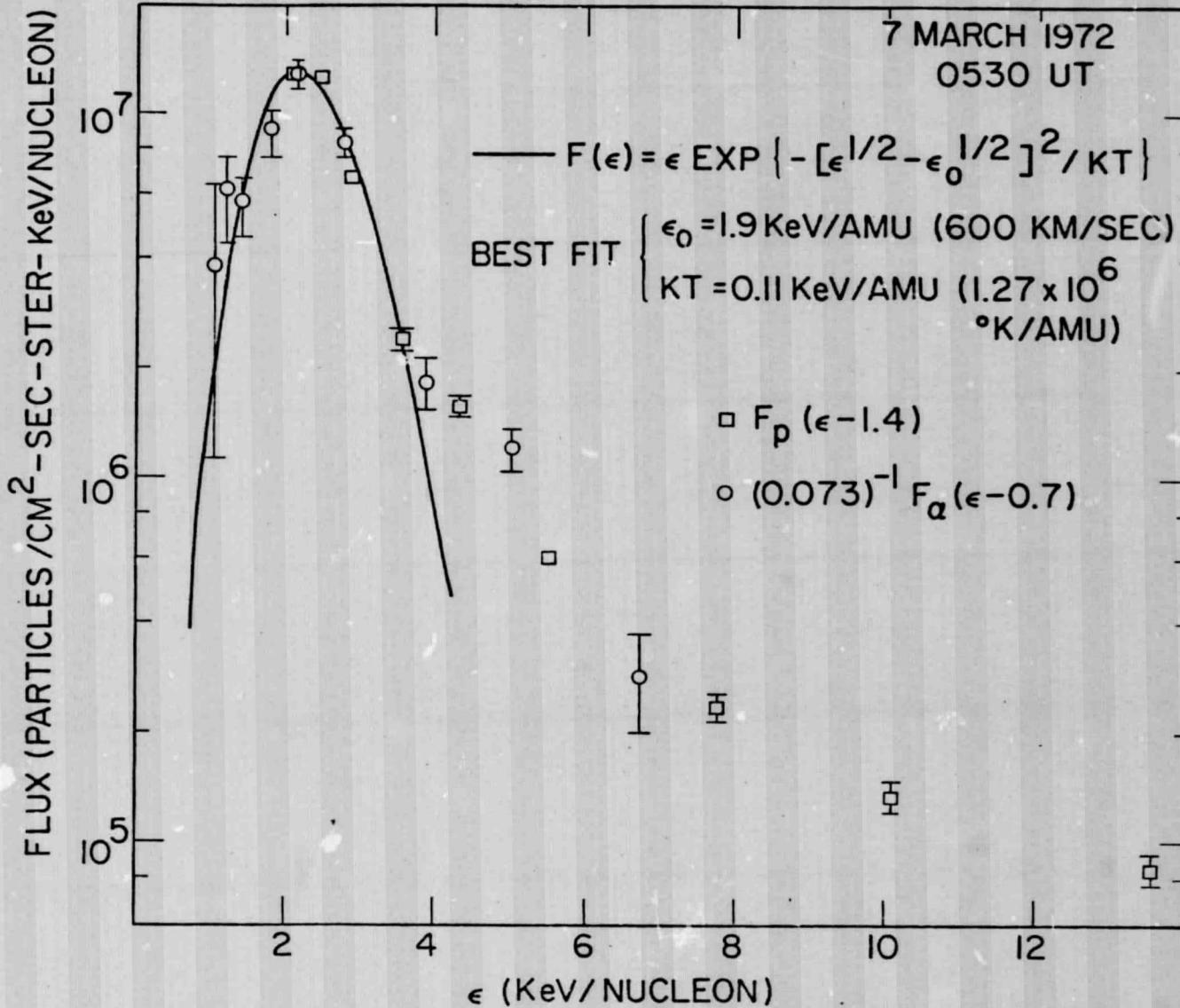


Figure 5. Composite He^{++} and H^+ energy per nucleon spectrum in the low-altitude cusp. The energy scales for the two ion species have been shifted by the energy change which would have resulted from a 1.4 kV potential barrier perpendicular to the flow direction (i.e., the electric field opposing the ion flow). The He^{++} spectrum has been multiplied by a factor $(1/0.073)$, implying a He^{++} to H^+ ratio of 7.3%. The solid curve is the best fit to a convecting Maxwellian distribution assuming the simultaneously measured solar wind speed of 600 km/sec.

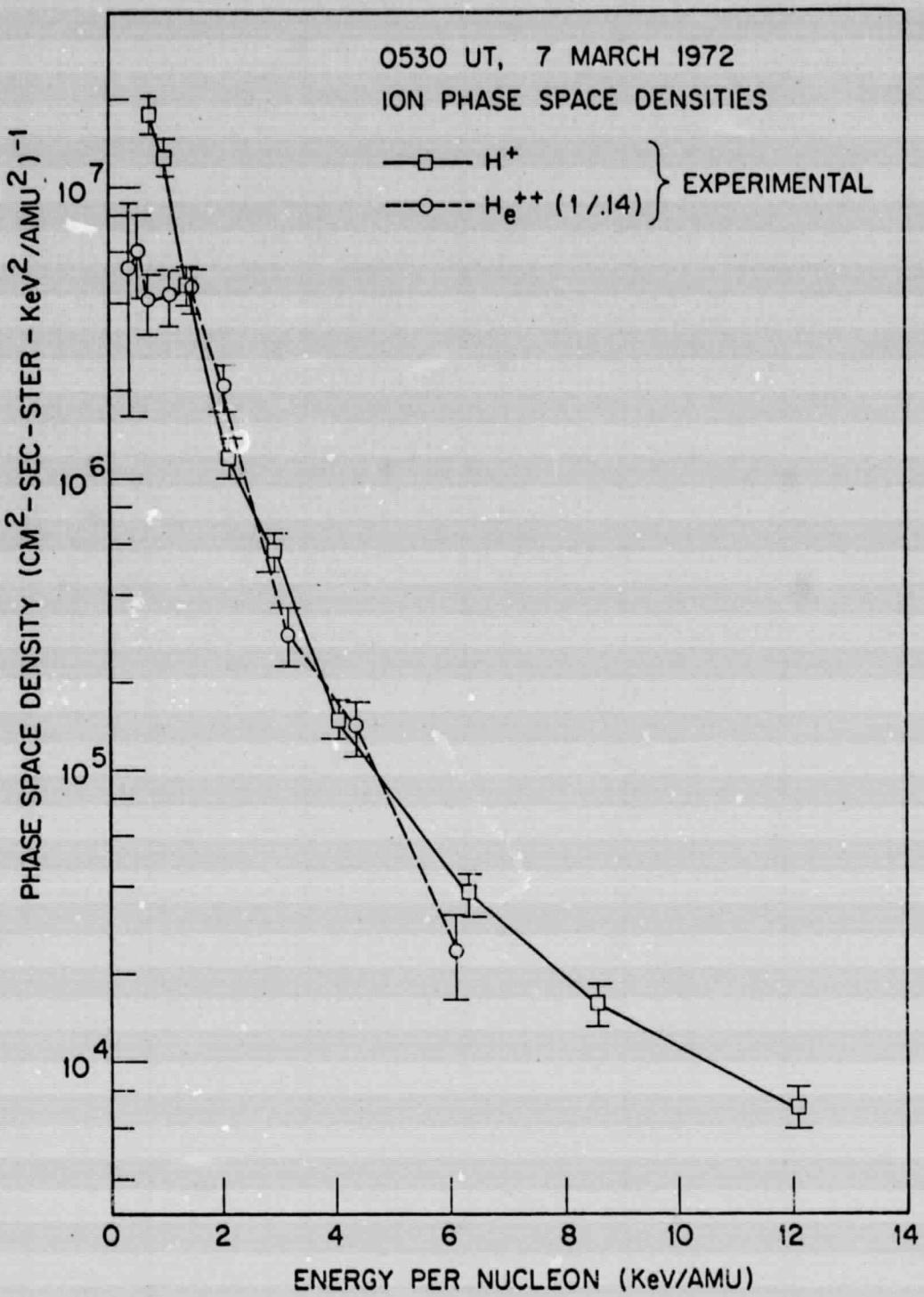


Figure 6. Relative phase space densities for the measured He⁺⁺ and H⁺ ions. Note that when the two species are normalized in the upper energy region there is a discrepancy of approximately 5 times in the lower energy region.

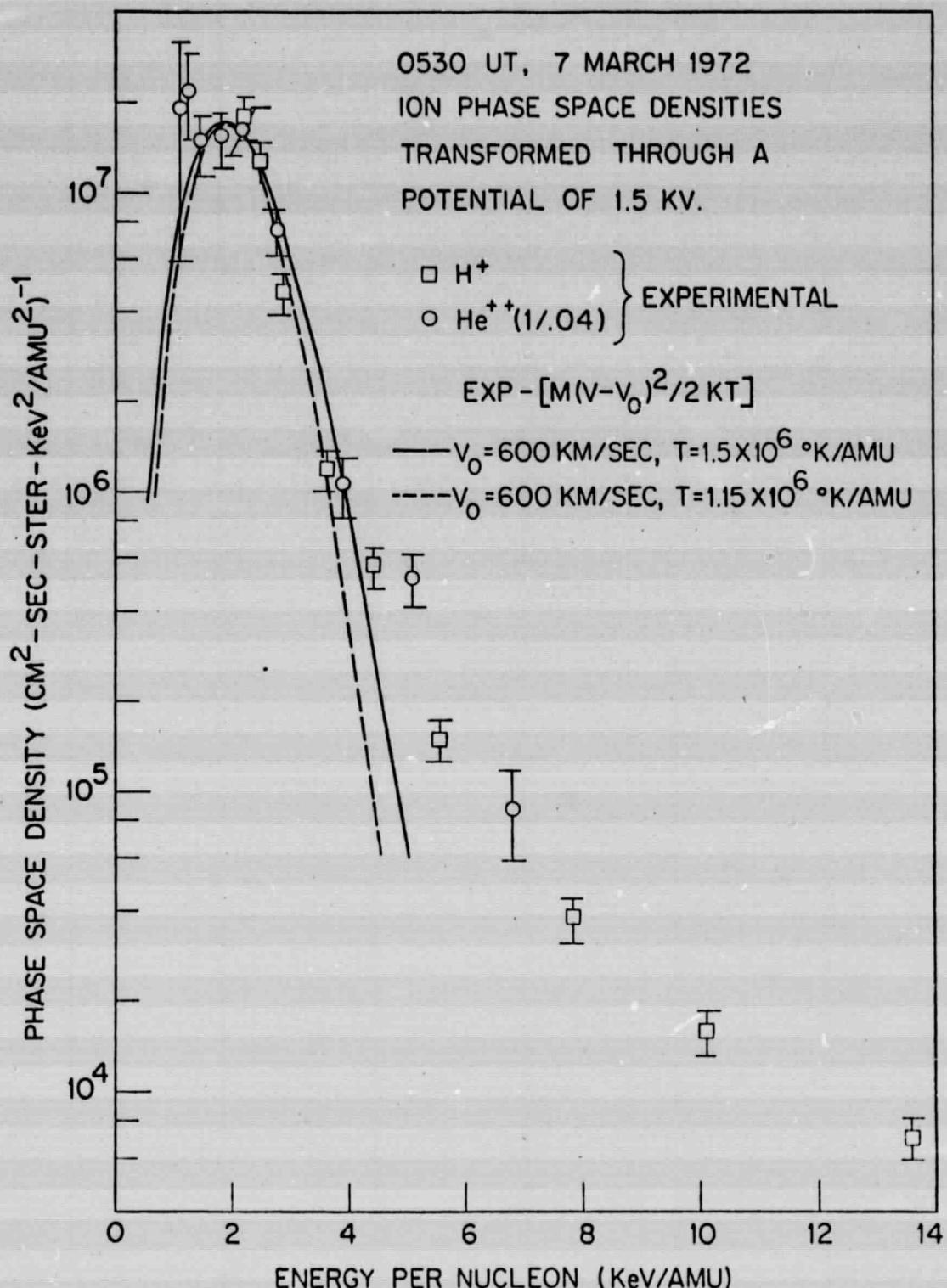


Figure 7. Relative phase space densities of He^{++} and H^+ after transforming the two spectra through a potential of 1.5 kV. The solid and dashed curves are the best convecting Maxwellian fits to the distribution for the He^{++} and H^+ respectively assuming the measured solar wind speed.

cusp if one assumes a different decelleration rate for H^+ than for He^{++} . An electrostatic decelleration would be a suitable possibility in agreement with previous observations in the bow shock.

In the course of the analysis of the mass spectrometer data during the 0530 UT traversal of the polar cusp on March 7, 1972, it was observed that the latitudinal distributions of the H^+ and He^{++} ions differed significantly. An investigation of this phenomenon led to the discovery of a new technique for deducing the dayside convection electric field from ion measurements in the low altitude cusp. This technique is described in a paper entitled, "He⁺⁺ and H⁺ Flux Measurements in the Dayside Cusp; Estimates of Convection Electric Fields", by E. G. Shelley, R. D. Sharp and R. G. Johnson which has been submitted to The Journal of Geophysical Research and is included as Appendix C. As discussed in the paper the utilization of this technique requires a detailed intercomparison of the mass spectrometer data with the data from the other auroral and high energy particle spectrometers on the 1971-89A satellite. Since this was beyond the scope of the present contract we pursued that aspect of the analysis under other funding.

As part of this project we surveyed the nightside auroral zone data for several time periods during which the solar wind parameters were relatively constant and one period during which a substantial enhancement in the average solar wind He^{++}/H^+ ratio was observed (\approx 04 hours UT on March 7, 1972). We concluded from these surveys that because of the reduced flux intensity, the higher average energy, and the enhanced penetrating background on the nightside, the detailed analysis of the nightside He^{++} data would have required more effort than was consistent with the limited resources available under this program. It was therefore decided to concentrate on the higher quality He^{++} data obtained during the traversals of the polar cusp. We concluded from our surveys of the cusp data during the period of the observed He^{++}/H^+ increase in the solar wind that there was indeed a corresponding enhancement at low altitudes. No substantial time delay was observed between the onset times of the observed enhancements at the two locations. These results will be written up for publication in The Journal of Geophysical Research.

SUMMARY AND CONCLUSIONS

A study of the simultaneously measured H^+ and He^{++} fluxes in the solar wind and in the magnetosphere has been undertaken utilizing IMP I and 1971-89A satellite data. A detailed analysis of the energy spectrums and latitudinal distributions of the ion fluxes during a traversal of the polar cusp on March 7, 1972, has resulted in the development of a new technique for deducing the dayside convection electric field and has allowed the inference of a potential difference of approximately 1.4 KV along the plasma flow direction between the observation points in the solar wind and the low altitude cusp.

REFERENCES

Johnson, R. G., R. D. Sharp, and E. G. Shelley. "The Discovery of Energetic He⁺ Ions in the Magnetosphere," J. Geophys. Res., 79, 3135, 1974.

Neugebauer, Marcia, "Initial Deceleration of Solar Wind Positive Ions in the Earth's Bow Shock," J. Geophys. Res., 75, 717, 1970.

Sharp, R. D., R. G. Johnson, and E. G. Shelley. "Satellite Measurements of Auroral Alpha Particles," J. Geophys. Res., 79, 5167, 1974.

Shelley, E. G., R. G. Johnson, and R. D. Sharp, "Satellite Observations of Energetic Heavy Ions during a Geomagnetic Storm," J. Geophys. Res., 77, 6104, 1972.

Shelley, E. G., R. G. Johnson, and R. D. Sharp, "Morphology of Energetic O⁺ in the Magnetosphere," in Magnetospheric Physics, B. M. McCormac, ed., p. 135, D. Reidel Publ. Co., Dordrecht, Netherlands, 1974.

APPENDIX A

DAYSIDE CONVECTION ELECTRIC FIELD DEDUCED
FROM ION MEASUREMENTS IN THE LOW-ALTITUDE CUSP

E. G. Shelley, R. D. Sharp, and R. G. Johnson
Lockheed Palo Alto Research Laboratory
Palo Alto, California 94304

ABSTRACT

Observations of protons and helium ions in the low-altitude cusp on March 7, 1972 show a significant energy dependence to the latitudinal distributions in the energy range from 0.7 to 12 keV per unit charge. The relative displacements of the low-altitude cutoff of the precipitating fluxes are found to be inversely proportional to the ion velocities. These observations are consistent with a dawn-to-dusk convection electric field, the magnitude of which can be estimated from the velocity dependence of the displacement. In the case discussed, the field was estimated to be approximately 50 mV/meter. This value is consistent with previous direct electric field measurements at high latitudes.

APPENDIX B

SIMULTANEOUS He^{++} AND H^+ OBSERVATIONS IN THE
SOLAR WIND AND THE LOW-ALTITUDE DAYSIDE CUSP

E. G. Shelley
Lockheed Palo Alto Research Laboratory
Palo Alto, California 94304

and

W. C. Feldman
Los Alamos Scientific Laboratory
Los Alamos, New Mexico 87544

ABSTRACT

During a magnetically active period on March 7, 1972, spectral measurements of the He^{++} and H^+ ion fluxes were made in the dayside cusp with a mass spectrometer on the polar-orbiting satellite 1971-089A at approximately 800 km altitude. The He^{++} and H^+ ion fluxes in the solar wind were simultaneously measured on the Imp-6 spacecraft near the earth. The energy-per-unit-charge range of the energetic ion mass spectrometer on board the polar-orbiting satellite was 700 eV to 12 keV. Within this range there was a clear maximum in the He^{++} energy spectrum at approximately 1.5 keV/nucleon. There was not a clearly-defined maximum in the H^+ spectrum, but the data were consistent with a peak between 0.7 and 1.0 keV/nucleon. Both spectra could be reasonably well fit with a convecting Maxwellian plus a high-energy tail; however, the mean velocity for the He^{++} distribution was significantly greater than that for the H^+ distribution. The simultaneous solar wind measurements showed the mean velocities for both ion species to be approximately 600 km/sec. The discrepancies between the relative velocity distributions in the low-altitude cusp and those in the solar wind are consistent with a potential difference of approximately 1.4 kV along their flow direction between the two points of observation.

B-1

Submitted to Journal of
Geophysical Research

-1-

A P P E N D I X C

He^{++} AND H^+ FLUX MEASUREMENTS IN THE DAYSIDE CUSP:
ESTIMATES OF CONVECTION ELECTRIC FIELD

E. G. Shelley, R. D. Sharp, and R. G. Johnson

July 1975

Space Sciences Laboratory
Lockheed Palo Alto Research Laboratory
Lockheed Missiles & Space Company, Inc.
3251 Hanover Street (52-12/205)
Palo Alto, California 94304

He⁺⁺ AND H⁺ FLUX MEASUREMENTS IN THE DAYSIDE CUSP:

ESTIMATES OF CONVECTION ELECTRIC FIELD

E. G. Shelley, R. D. Sharp, and R. G. Johnson
LOCKHEED PALO ALTO RESEARCH LABORATORY
Palo Alto, California 94304

ABSTRACT

Ion mass spectrometer measurements of He⁺⁺ and H⁺ ion spectra in the energy-per-unit-charge range between 0.7 and 12 keV in the low-altitude dayside cusp (~ 800 km) show a systematic velocity dependence in the latitudinal distributions. This dependence is explained by a dawn-dusk convection electric field of 30 to 60 mV/m operating in the cusp. The average velocity spectrum of the He⁺⁺ is found to be significantly harder than the accompanying H⁺ spectrum suggesting the possibility of an electrostatic deceleration mechanism operating between the solar wind source region and the low-altitude cusp.

INTRODUCTION

The satellite 1971-089A carried a set of energetic ion mass spectrometers which made measurements of precipitating auroral ions in the energy range from 0.7 to 12 keV per unit charge. Sharp et al. [1974] recently reported on observations of nightside He^{++} ions by this experiment. Earlier reports of O^+ ion observations [Shelley et al., 1972, 1974a; Johnson et al., 1975] and He^+ ion observations [Johnson et al., 1974] by this experiment have also been given. In this paper we present an example of simultaneous H^+ and He^{++} ion observations in the dayside cusp. Preliminary reports on these dayside observations were given by Shelley et al. [1973, 1974b] and Shelley and Feldman [1975].

Previous measurements of low-energy charged particle distributions in the cusp [Heikkila and Winningham, 1971; Frank, 1971; Burch, 1972; and Yasuhara et al., 1973] have provided convincing evidence for the direct access of magnetosheath particles into the cusp region and have demonstrated significant correlations between the location of the cusp and various indicies of geomagnetic activity. These earlier measurements however did not include the determination of the ion composition and thus lumped all positive ion fluxes together as "proton" fluxes.

The motivation for making mass spectroscopic measurements in the magnetosphere has been discussed by Axford [1969, 1970], Cornwall [1972], Johnson et al. [1975], and others. Since helium ions in the solar wind are predominately doubly charged and those in the ionosphere are singly charged, the observations that the helium ions in the cusp are doubly

charged and that the $\text{He}^{++}/\text{H}^+$ ratio is consistent with solar wind ratios provided unambiguous evidence for the solar wind origin of these fluxes [Shelley et al., 1973]. In addition, the measurement of the relative energy distribution functions for H^+ and He^{++} in the cusp can provide valuable information on the possible transport and acceleration processes acting on the particles during their transit from the solar wind to the low-altitude cusp, and this paper primarily addresses these points.

INSTRUMENTATION

The satellite 1971-089A was in a nearly circular orbit at 800 km altitude with an inclination of 93° . It was gravity-gradient stabilized and the three mass spectrometers were continuously oriented at 55° with respect to the local zenith. Each spectrometer consisted of a crossed-field velocity filter in series with an electrostatic analyzer with a channel-electron-multiplier utilized as a sensor. The combination of energy-per-unit-charge and velocity analyses disperses the incident ions into a mass-per-unit-charge spectrum. Such spectrums were acquired at each of nine energies every six seconds. The energies were 0.74, 1.01, 1.41, 2.14, 2.92, 4.07, 6.3, 8.6, and 12.1 keV per unit charge. A more detailed description of the experiment is given by Shelley et al. [1972]. The 1971-089A payload included a large complement of particle detectors in addition to the three mass spectrometers. We will be discussing data from a group of low-energy electron and proton analyzers using channel-electron-multipliers as sensors plus a pair of plastic scintillator electron spectrometers covering the range from 130 keV to

1 MeV [Imhof et al., 1973]. The low-energy electron analyzers were broad-band ($\Delta E/E$ of 0.6-1.1), 180° permanent magnet spectrometers. The energy range from approximately 60 eV to 40 keV was covered in nine contiguous bands at 55° to the zenith and the same energy range was covered in seven contiguous bands at 15° to the zenith. Protons in the energy band between 1.2 and 3.6 keV were measured at both of the above zenith angles by permanent magnet spectrometers. These magnetic spectrometers perform momentum analysis only and thus are sensitive to the He^{++} ions in this same energy range. However, since the He^{++} contributes less than 10% to the flux, it will be neglected for the use of the data from this sensor. In addition, protons with energies greater than 16 keV and greater than 39 keV were measured at 55° zenith angle by two thin-foil threshold detectors with broom magnets for electron rejection. A similar detector with a 39-keV threshold was also operated at the 15° zenith angle. Again, we point out that these detectors are sensitive to ion species other than H^+ ; however, the energy threshold is significantly higher for heavier ions due to the greater energy loss in the foils. Since the measured spectrum is relatively soft, ion species other than H^+ are not thought to be contributing significantly to these detector responses. Detectors of the above types have been described in more detail by Shea et al. [1967], Reed et al. [1969] and Paschmann et al. [1970].

The integral electron fluxes from the two energetic electron spectrometers, one at 20° zenith angle and one at 90° zenith angle, will be used as indicators of the electron trapping boundary.

An on-board three-axis magnetometer provided in situ determination of the instantaneous pitch angles for all detectors.

OBSERVATIONS

General observations and geophysical conditions. We will be discussing the charged particle observations from the above complement of detectors during a pass through the cusp region at about 0530 UT on 7 March 1972. The magnetic local time was ~ 1115 . The observations were during the main phase of a small magnetic storm, $Dst \approx -70$ gamma, which began with a sudden commencement at about 2100 UT on 6 March. The K_p index was 6° for the three-hour period which included the cusp crossing. The AE index was increasing during this period with an average value of approximately 400 gamma for the period 0500 to 0600 UT.

Figure 1 shows the latitudinal dependence of the particle fluxes in several energy ranges. Note that the scales are logarithmic and each panel covers several decades. The top five panels show the low-energy differential electron fluxes observed at 55° zenith angle ($\sim 52^{\circ}$ pitch angle). The electron fluxes in the range between 3.3 keV and 40 keV were below the sensitivity range of the detectors, i.e., $\Phi(E) \leq 10^5 / E (\text{cm}^2 \cdot \text{sec} \cdot \text{ster} \cdot \text{keV})^{-1}$. The sixth panel from the top is the differential proton flux near 52° pitch angle in the energy range between 1.2 and 3.6 keV as measured by the magnetic spectrometer. (As discussed in the previous section, this detector is also sensitive to all other positive ions of equivalent momentum per unit charge.) The next panel shows the average differential proton flux in the 0.74 to 12.1 keV range as measured by the mass spectrometers. The absolute flux

difference between this panel and the one above results from the fact that the energy spectrum of the protons is relatively soft and the magnetic spectrometer is centered near the peak flux while the mass spectrometer results are averaged over a 12-keV range. The integral proton fluxes above 16 keV and 39 keV as measured by foil threshold detectors are shown in the next two panels. The bottom panel shows the trapped and precipitating energetic electrons. The universal time and the invariant latitude are indicated along the abscissa. The vertical dashed line between 0531 and 0532 UT indicates our determination of the energetic electron trapping boundary, defined as the point at which the > 130-keV electrons become isotropic. This "trapping boundary" will be used in the other figures as a reference mark.

As described above, similar measurements to those just described were also made at 15° zenith angle ($\sim 13^{\circ}$ pitch angle). In spite of the large spatial variation in the absolute magnitude of the fluxes over the cusp region, there were no large differences in the fluxes measured at the two angles. On the basis of the preflight calibrations of the detector sensitivities, the average anisotropy, $\Phi(13^{\circ})/\Phi(52^{\circ})$, of both the 1.2-3.6 keV protons and the total low-energy electron flux was 1.2. However, these results are not inconsistent with isotropy within the accuracy of the inter-calibrations. The > 39-keV proton fluxes were also consistent with isotropy above the "trapping boundary", but below this boundary the average flux at 52° pitch angle was a factor of two greater than the flux at 13° pitch angle, indicating a trapped magnetospheric proton distribution.

As discussed by Sharp et al. [1974], the mass dispersion of each spectrometer is such that the He^{++} and H^+ fluxes are not completely separated

and therefore a stripping procedure using the instrument resolution functions must be employed to accurately determine the He^{++} flux intensities. The procedure has been described in more detail in the above-cited reference. Figure 2 shows a representative example of the raw spectrometer data and the analytically-determined flux intensities of H^+ and He^{++} . The spectrometer measures the strength of the mass dispersed ion fluxes at 64 points for each energy measured. The open circles in Figure 2 are the counting rates measured at each of these points and the vertical bars represent the counting statistics associated with each point. The solid curve is the least squares fit to the data obtained by adjusting the strengths of the He^{++} and H^+ fluxes. The dashed lines show the expected responses for pure He^{++} or pure H^+ in the respective strengths determined from the fitting procedure. It was possible to also include several additional mass components and a uniform penetrating background in the fitting routine. In this case, however, the data were consistent with zero penetrating background and relatively low fluxes of ions heavier than He^{++} . The latter had no significant influence on the determination of the H^+ and He^{++} strengths and will not be discussed here. One obtains a flux determination of He^{++} and H^+ at each of nine energies every six seconds.

Cusp location. Figure 3 shows the integrated flux over the energy range of the spectrometers for both mass components as a function of UT and invariant latitude. The trapping boundary location has been included for reference. The two mass components are clearly observed over the same general range of latitude. The low-latitude edge coincides with the trapping boundary and the low-latitude edge of the soft electrons within the spatial resolution of the measurements ($\Delta\Lambda \approx 1/2^\circ$). On the basis of this

combination of observations we place the low-latitude edge of the cusp at approximately 70.8° invariant. This location is consistent with the observations of Yasuhara et al. [1973] for periods during magnetic storms when there is significant Dst. As seen from Figure 1, the soft electrons are very structured and extend into the polar cap region with no distinctive feature which can be clearly identified as the high-latitude limit of the cusp. The difficulty in establishing the high-latitude edge of the cusp from the soft electron fluxes has been discussed previously by Burch [1972]. As shown in Figures 1 and 3, the high-latitude extent of the positive ion fluxes is discernible, though less sharply so than is the low-latitude limit. It is known that the positive ion flux spectra in the cusp typically peak at energies below 0.7 keV (our lowest energy channel) [Frank, 1971; Heikkila and Winningham, 1971], and as we shall see below, the latitudinal distributions of the ions are energy dependent. However, within the constraints of the available data, we can reasonably establish the high-latitude edge of the cusp as $74^\circ \pm 0.5^\circ$ on the basis of the positive ions. This leads to a cusp width of $3.2^\circ \pm 5^\circ$, consistent with the results of Winningham [1972].

Poleward convection in the cusp. In the previous section we described the He^{++} and H^+ ions as precipitating in the same general range of latitude; however, the detailed latitudinal distributions of the two ion species differ significantly as can be seen in Figure 3; the linear scale emphasizes these differences. The maximum in the integral H^+ flux is displaced approximately 0.6° poleward from the maximum in the integral He^{++} flux.

In Figure 4 we show the latitudinal distributions of the relative ion fluxes within individual energy channels of the spectrometers. For ease of intercomparison, we have plotted the H^+ and He^{++} fluxes of the same energy per unit mass (i.e., the same velocity) with the same symbols. To avoid confusion, only three of the nine energy groups measured for each ion species have been included. When the data are viewed in this format the systematic dependence of the latitudinal distributions on ion velocity is very evident. The slower particles are displaced poleward relative to the faster particles; this is particularly evident in the low-latitude cutoff of each velocity group.

This systematic displacement can be explained in terms of the mechanism proposed by Rosenbauer et al. [1975] to explain the spatial distributions of the plasma mantle. It is generally agreed that the source for these ions is the magnetosheath. In an open magnetosphere with reconnection, magnetosheath ions of all energies (velocities) simultaneously gain access to the cusp along newly interconnected field lines. At the same time that these ions are traversing the distance between the merging point in the magnetosheath and the low-altitude cusp region, the field lines are being convected poleward. This is shown schematically in Figure 5 taken from Rosenbauer et al. [1975]. In this figure the solid circles represent ions with relatively high velocities while the open circles represent ions with lower velocities. The sequence of similar symbols represents the trajectories of the ions with respect to the magnetic field configuration. The lowest latitude to which a given ion group has access at low altitude is a function of the distance the field line (acting as a guiding center

for the ions) has convected in the time required for that ion group to travel the distance from the source point to the observation point. This low-latitude limit is relatively independent of the actual latitudinal width of the source region. At higher latitudes there is a composite mixture of various energy ions from different source points at the top of the cusp. As discussed by Rosenbauer et al. [1975], the proposed mechanism does not in fact require either an open magnetosphere or reconnection. It does, however, require direct access for the plasma at the top of the cusp in the vicinity of the neutral points.

If the proposed mechanism is the explanation for the observed distributions, the relative positions of the low-latitude limits of the individual ion groups should be directly proportional to the time of flight of the ions from the source region to the observation point or inversely proportional to the ion velocities. That this is in fact the case is shown in Figure 6 where the low-latitude limit of each ion group is plotted against its relative inverse velocity in units of $(\text{AMU}/\text{keV})^{1/2}$. In order to minimize biases which might otherwise result from differences in flux levels relative to detector background and from differences in the locations at which particular ion groups were measured relative to the flux maxima, we have defined the low-latitude limit of each velocity group as the position at which the flux has dropped to 10% of the average of the three highest flux measurements for that group. Since each ion group was measured only once every six seconds, (i.e., approximately 1/2 degree in latitude) the limit was determined by linear interpolation between measurements on a semi-log plot similar to those of Figure 4. The symbols, open circles for He^{++} and solid circles for H^+ , in

Figure 6 represent the interpolated locations of the limits and the horizontal bars indicate the six-second time resolution of the measurements. It should be noted that these bars are not to be interpreted as one sigma statistical uncertainties, but rather as bounds on possible errors in location of the limits resulting from the finite time resolution of the measurements. In addition to the mass spectrometer data we have included similar low-latitude limits determined from other particle detectors. These other detectors had much better time resolution and thus the uncertainties in the low-latitude limits were not significant.

It is clear from Figure 6 that the mass spectrometer observations are indeed very much in agreement with the predictions of the proposed mechanism. The solid diagonal line represents a best eye-ball fit to these data. The measurements from the magnetic spectrometer, sensitive to protons with a mean energy of approximately 2.4 keV, are also in excellent agreement with the model. We note, however, that the more energetic protons as measured by the threshold detectors, deviate from the straight line toward lower latitudes. The energies for these protons were assumed to be equal to the energy thresholds of the detectors plus one unit of the e-folding energy determined from the two-point integral measurements. One might well expect such a deviation toward lower latitudes since these ions are presumably primarily from the magnetospheric population; it was noted earlier that the more energetic protons were observed to have a trapped angular distribution below the energetic electron trapping boundary. By this same reasoning we might anticipate that some of the more energetic protons measured by the mass spectrometer were also contributed to from magnetospherically trapped

distributions, thus biasing these measurements to somewhat lower latitudes. Such trapped ions could be scattered into the loss cone in the turbulent magnetopause and cusp regions; some of these ions could be precipitated out while most were lost to the magnetosheath at the open end of the flux tube. Solar protons with energies greater than 1 MeV were also observed over the polar cap region and extended below the "trapping boundary", but the solar protons were not thought to be contributing significantly to the measurements discussed above because the intensities of these fluxes relative to the solar protons decreased substantially over the polar cap.

The magnetosheath-like soft electrons appear to be shifted poleward by approximately 1/2 degree in latitude relative to the position predicted on the basis of their velocity. This may result partially from the above-discussed contribution to the ions from magnetospheric sources, but may also result from the fact that the low-energy electrons can be expected to be much more severely scattered during their traversal from the magnetosheath to the low-altitude region and thus their effective velocities parallel to the field line may be significantly reduced. This explanation, however, is difficult to reconcile with the relatively sharp low-latitude boundary of these soft electrons and the near coincidence of the boundary for electrons of somewhat greater energies (see Figure 1).

The position of the energetic electron trapping boundary has also been included in Figure 6 as a reference point. We note, however, that the location of the "trapping boundary" is somewhat arbitrary in that it depends on the definition utilized. In this case, it was defined as the position where the $E > 130$ keV electrons become isotropic. As seen in Figure 1, the ener-

getic electron flux is actually observed at a low level above this boundary up to about 72.8° , but remains isotropic. There is at present some question as to what definition of the trapping boundary is appropriate as the delineation of the limit of closed field lines [McDiarmid et al., 1972, 1975; Vasyliunas, 1974]

It appears to be necessary to either explain the existence of these low-intensity energetic electrons, sometimes with trapped distributions [Burrows et al., 1972; McDiarmid et al., 1972, 1975] on open field lines or to conclude that a significant portion of the cusp region is on closed field lines. For the purposes of the present discussion, we take the former approach and assume that these energetic electron fluxes, which are isotropic and represent only a small fraction of the lower-latitude trapped fluxes (see Figure 1), are on open field lines which penetrate the magnetopause [see Hones et al., 1972].

In the framework of the model described above, one can estimate the poleward convection velocity within the cusp from the slope of the diagonal line in Figure 6 and the assumed distance to the source point in the magnetosheath. The speed of the ions (in km/sec) is given approximately by:

$$v_i(E,M) = 440 (E/M)^{1/2}$$

where E is in keV and M is in AMU. Since ions observed at low altitude with pitch angles of approximately 55° would have traveled nearly parallel to the magnetic field lines over most of their path from the magnetosheath, we will neglect the effects of changing pitch angle and assume that the parallel

velocity is equal to the total ion velocity. With this assumption the time of flight of the ions in seconds is given approximately by:

$$\tau = 14.5 R (E/M)^{-1/2}$$

where R is the particle path length in earth radii from the source. The horizontal displacement of a field line at the ionosphere is given by:

$$H = V_c \tau = V_c 14.5 R (E/M)^{-1/2}$$

where V_c is the convection velocity (in km/sec) and H is the horizontal displacement in km. Thus:

$$V_c = \frac{1}{14.5R} \left[\frac{\Delta X}{\Delta Y} \right]$$

where $\Delta X/\Delta Y$ is the inverse of the slope of the diagonal line in Figure 6 and ΔX is measured in km. The line shown corresponds to a convection velocity 1.50 km/sec if one assumes a $10 R_E$ distance for the source region. This is a reasonable value if the plasma entry is immediately at the top of the cusp; however, if the initial access is at the sub-solar point on the magnetopause, a field line length of approximately $18 R_E$ is more reasonable. This greater distance would imply a convection velocity of approximately 0.83 km/sec. The corresponding electric field (in mV/m) is given by

$$E = 10^{-3} V_c B$$

where B is in gamma. Using $B = 4 \times 10^4$ gamma at 800-km altitude, we calculate a dawn-to-dusk electric field of 60 mV/m and 33 mV/m for source distances of $10 R_E$ and $18 R_E$, respectively. This range of convection electric fields is in agreement with the reported values of high-latitude electric fields [Haerendel, 1972; Mozer et al., 1974].

The mechanism described here can explain the hardening of the "proton" spectrum at the low-latitude edge of the cusp reported by Heikkila and Winningham [1971]; however, their observation that sometimes there is also hardening at the high-latitude edge is not explained. Frank [1971] has reported a persistent latitudinal separation between a "proton sheet" and "electron sheet" in the mid-altitude cusp with the proton sheet poleward of the electron sheet. The average magnitude of this separation was not given, but the direction of separation is consistent with the mechanism described here. The one example given in Figure 16 of Frank [1971] suggests a separation of less than one degree in invariant latitude; this is of the correct order of magnitude to be accounted for by this mechanism.

Ion energy spectra. It is clear from Figure 4 that the energy spectra of the cusp ions vary as a function of latitudinal position within the cusp. Heikkila and Winningham [1971] discussed the softening of the positive ion spectrum toward the middle of the cusp region. In the last section the hardening toward the low-latitude edge of the cusp was explained by the poleward convection of the cusp field lines acting as a velocity selector for the magnetosheath particles entering the cusp. Given the spectral distortions resulting from this mechanism, it would be inappropriate to select any given location in the low-altitude cusp to define the ion spectra as

representative of the magnetosheath source region. However, assuming equal access to the cusp for all ions in the sheath source region, the spectra averaged over latitude in the low-altitude cusp should be most directly representative of the source region except for processes occurring during the transport from the source region to the observation point. In Figure 7 we show the He^{++} and H^+ energy-per-nucleon spectra averaged over the entire cusp region (0531:20 UT to 0532:34 UT). This averaging reduces the absolute flux intensity by approximately a factor of five from the peak values for both species (see Figure 3).

The error bars on the data points in Figure 7 show the counting statistics only; there is an estimated additional relative uncertainty of approximately 10-15% between data points resulting from relative uncertainties in the energy and mass dependence of the spectrometer sensitivities. There are also uncertainties of the order of 20% or less in the He^{++} fluxes resulting from inaccuracies in the mass spectrum fitting procedures. We note from Figure 7 that even in an energy-per-nucleon (i.e., velocity) space, the He^{++} spectrum is harder than the H^+ spectrum. Clearly, in an energy-per-charge space, or total energy space, the hardness of the He^{++} spectrum relative to the H^+ spectrum would be significantly enhanced. Comparing these results with previously reported observations of H^+ and He^{++} spectra over this energy range in the magnetosphere, we find better agreement with the results of Sharp et al. [1974] that the ions have approximately the same velocity distributions than with the findings of Whalen and McDiarmid [1972] that the energy-per-charge spectra are similar. Both of these earlier observations were on the nightside of the magnetosphere. Examination of the spectra in Figure 7

show a clear maximum in the He^{++} spectrum at approximately 1.5 keV/AMU. No definite maximum is observed in the H^+ spectrum in the energy range covered; however, the data are consistent with a maximum between 0.7 and 1.0 keV. A maximum in the H^+ cusp spectrum in this energy range is consistent with Frank [1971, see his Figure 11], but is approximately a factor of two higher in energy than the average reported by Heikkila and Winningham [1971]. This may be accounted for by the high solar wind speed of approximately 600 km/sec at this time (W. C. Feldman, private communication). The important observation here is that the He^{++} spectrum peaks at a significantly higher energy per nucleon than does the H^+ spectrum. This implies a higher mean speed for the He^{++} .

It should be noted that all of the ions observed at these low altitudes will map into very small pitch angles in the high-altitude cusp and therefore correspond to fluxes traveling nearly parallel to the field lines in the vicinity of the magnetosheath, neglecting effects of pitch-angle scattering. It is reasonable to assume that the plasma flow in the magnetosheath near the noon meridian is nearly parallel to the magnetopause up stream from the cusp and therefore essentially parallel to the last closed field line or most recently-merged field line. Thus plasma observed in the low-altitude cusp would be expected to represent a sample of the magnetosheath plasma looking nearly into the flow direction, assuming this magnetosheath plasma is guided by the recently-merged magnetospheric field lines. Assuming a convecting Maxwellian distribution in the magnetosheath source region, the energy-per-nucleon flux spectrum along the flow direction has the form:

$$F(\epsilon) \propto \epsilon \exp \left[-\left(\epsilon^{1/2} - \epsilon_0^{1/2} \right)^2 / \tau \right]$$

where ϵ is the total energy per nucleon, ϵ_0 is the bulk flow energy per nucleon and τ is the thermal energy per nucleon.

The solid curves in Figure 7 are of the form given above, but with the temperature and bulk speed parameters given in the more conventional units of km/sec and $^{\circ}$ K. We note that the lower-energy portions of both spectra are reasonably well fit by the distribution. The fit to the H^+ spectrum is not particularly sensitive to the choice of parameters; however, a reasonable fit to both spectra cannot be obtained with the same parameter set. In particular, the data are not consistent with the same bulk speed parameter. We note that the temperature ratio (T_{α}/T_p) of 3.1 is reasonably consistent with typical temperature ratios in the solar wind [Feldman et al., 1974; Hirshberg et al., 1974; Robbins et al., 1970]. No measurements of the temperature ratios have been reported in the magnetosheath.

The bulk speeds of the H^+ and He^{++} are known to be approximately equal in the solar wind, as in fact was the case at this time (W. C. Feldman, private communication). The difference in bulk speeds between the two ion species observed at low altitudes suggests a possible electrostatic deceleration process operating somewhere between the solar wind and the low-altitude cusp.

A more detailed study of the relationship between the solar wind plasma parameters and the low-altitude cusp observations is presently in progress.

Helium-hydrogen ratio. A commonly referred to parameter in studies of energetic He^{++} and H^+ ions in the magnetosphere is the ion density ratio.

This ratio is then compared with the typical ratio of approximately 4% in the solar wind. We note from Figure 4 that this ratio is clearly a function of position within the cusp, and on the basis of this integral flux over the same energy-per-unit-charge range, the flux ratio varies between 3% and 30%. The translation of these flux ratios to number density ratios would require knowledge of the individual spectral parameters at each location.

Considering the spectral distortions which would be generated in the low-altitude cusp by convection (as discussed in the last section), a more appropriate ratio may be expected from the latitudinally averaged spectra. Referring to Figure 7, we note that the number density ratio is equal to the flux ratio at the same energy per nucleon (velocity). Again, this ratio varies significantly over the range of overlapping measurements, ranging from approximately 3% to 25%.

If we postulate a mechanism which shifts one spectrum relative to the other, such as an electrostatic field, the ratios of maximum densities in phase space may be a more appropriate parameter for comparison with the typical solar wind ratio. Assuming the spectra given by the solid curves in Figure 7, this ratio is approximately 4%, in good agreement with typical solar wind ratios.

Finally, the ratio of the integral number densities over the range of measurement (which does not cover the low end of the typical cusp proton spectra) is approximately 8%. We conclude that within the limitations of our knowledge of the transport and acceleration processes operating between the solar wind and the low-altitude cusp, the measured alpha-proton ratios

are consistent with typical solar wind values. However, the wide range of values for this ratio obtained above clearly indicates the need for caution in interpreting such ratios and demonstrates that the direct ratio of ion fluxes at the same energy per nucleon (velocity) is not necessarily the correct parameter to be compared with density ratios in the source region.

SUMMARY AND CONCLUSIONS

The observation of He^{++} ions in the low-altitude cusp with densities relative to the accompanying H^+ consistent with solar wind ratios provide additional support to the conclusion that magnetosheath plasma has direct access to the cusp field lines. By utilizing the measurements of both ion species we have demonstrated for the case studied that the locations of the low-latitude limits of precipitation are linearly related to the inverse velocities of the ions. We have interpreted these observations in terms of a model previously proposed by Rosenbauer et al. [1975] to explain the creation of the plasma mantle. In this model the magnetosheath plasma gains direct access to cusp field lines and is velocity-dispersed at low altitude by the effects of anti-sunward convection. Electric fields in the range 30 to 60 mV/m are required to fit the present data and these are consistent with direct electric field measurements at high latitudes [Mozer et al., 1974]. We discussed this process in terms of an open magnetosphere with the plasma gaining access through field line merging at the magnetopause; however, we note that the process does not require an open magnetosphere but is consistent with any process which provides direct access to

the cusp field lines for the magnetosheath plasma. This proposed mechanism explains the general hardening of the positive ion spectrum at the low-latitude edge of the cusp previously reported by Heikkila and Winningham [1971] and is also consistent with the observed separation of the proton and electron sheets reported by Frank [1971].

We have also shown that at least in this one case the mean velocity of the He^{++} ions is significantly greater than that of the H^+ ions. This suggests a deceleration process, such as an electrostatic field, operating between the solar wind source region and the low-altitude cusp which slows down the H^+ ions relatively more than the He^{++} ions.

This single observation may not be typical in all respects in that the mean energies of the ions was significantly greater than the "typical" values reported by Heikkila and Winningham [1971] and may have resulted from the unusually high solar wind speed. Unfortunately, the energy range of the present energetic-ion-mass-spectrometer does not extend down to the "typical" proton energies in the cusp.

Finally we note that one must consider the transport and energization processes operating on the plasma between two observation regions in interpreting the comparison of plasma density ratios. The common practice of comparing density ratios at the same energy per nucleon or velocity is only valid if the processes do not alter the relative speeds of the two ion species. Specifically, if electrostatic processes are acting, then such a comparison is invalid.

ACKNOWLEDGMENTS

The authors wish to thank Dr. W. C. Feldman for providing previously unpublished solar wind data from the P-6 spacecraft. We also wish to express our gratitude to Drs. W. L. [redacted] and J. B. Reagan for use of unpublished data from the 1971-089A spacecraft and Mr. D. L. Carr for the data reduction.

This analysis has been supported by the Atmospheric Sciences Section of the National Science Foundation and the National Aeronautics and Space Administration under Contract NASW 2554. The satellite experiment was supported by the Defense Nuclear Agency and the Office of Naval Research.

REFERENCES

Axford, W. I., Helium in the atmosphere, aurora and solar wind, in Atmospheric Emissions, B. M. McCormac, ed., Reinhold, New York, p. 317, 1969.

Axford, W. I., On the origin of radiation belt and auroral primary ions, in Particles and Fields in the Magnetosphere, B. M. McCormac, ed., D. Reidel Publ. Co., Dordrecht-Holland, p. 46, 1970.

Burch, J. L., Precipitation of low-energy electrons at high latitudes: effects of interplanetary magnetic field and dipole tilt angle, J. Geophys. Res., 77, 6696, 1972.

Burrows, J. R., I. B. McDiarmid, and Margaret D. Wilson, Pitch angles and spectra of particles in the outer zone near noon, in Earth's Magnetospheric Processes, B. M. McCormac, ed., D. Reidel Publ. Co., Dordrecht-Holland, p. 153, 1972.

Cornwall, J. M., Radial diffusion of ionized helium and protons: a probe for magnetospheric dynamics, J. Geophys. Res., 77, 1756, 1972.

Feldman, W. C., J. R. Asbridge, and S. J. Bame, The solar wind He^{2+} to H^+ temperature ratio, J. Geophys. Res., 79, 2319, 1974.

Frank, L. A., Plasma in the Earth's polar magnetosphere, J. Geophys. Res., 76, 5205, 1971.

Haerendel, G., Electric fields and their effects in the ionosphere, in Solar Terrestrial Physics/1970, E. R. Dyer, ed., D. Reidel Publ. Co., Dordrecht-Holland, p. 87 (Part IV), 1972.

Heikkila, W. J., and J. D. Winnigham, Penetration of magnetosheath plasma to low altitudes through the dayside magnetospheric cusps, J. Geophys. Res., 76, 883, 1971.

Hirshberg, J., J. R. Asbridge, and D. E. Robbins, The helium component of solar wind velocity streams, J. Geophys. Res., 79, 934, 1974.

Hones, E. W., Jr., S.-I. Akasofu, S. J. Bame, and Sidney Singer, Outflow of plasma from the magnetotail into the magnetosheath, J. Geophys. Res., 77, 6688, 1972.

Imhof, W. L., E. E. Gaines, and J. B. Reagan, Dynamic variations in intensity and energy spectra of electrons in the inner radiation belt, J. Geophys. Res., 78, 4568, 1973.

Johnson, R. G., R. D. Sharp, and E. G. Shelley, The discovery of energetic He⁺ ions in the magnetosphere, J. Geophys. Res., 79, 3135, 1974.

Johnson, R. G., R. D. Sharp, and E. G. Shelley, Composition of the hot plasmas in the magnetosphere, Proceedings of the Nobel Symposium on the Physics of the Hot Plasma in the Magnetosphere, Kiruna, Sweden, to be published by Plenum Publishing Company, Ltd., 1975.

McDiarmid, I. B., J. R. Burrows, and Margaret D. Wilson, Solar particles and dayside limit of closed field lines, J. Geophys. Res., 77, 1103, 1972.

McDiarmid, I. B., J. R. Burrows, and E. E. Budzinski, Particle properties in the dayside cleft, Preprint Division of Physics, National Research Council of Canada, Ottawa, Canada K1A OR6, 1975.

Mozer, F. S., W. D. Gonzales, F. Bogott, M. C. Kelley, and S. Schultz, High-latitude electric fields and three-dimensional interaction between the interplanetary and terrestrial magnetic fields, J. Geophys. Res., 79, 56, 1974.

Paschmann, G., E. G. Shelley, C. R. Chappell, R. D. Sharp, and L. F. Smith,
Absolute efficiency measurements for channel-electron-multipliers
utilizing a unique electron source, Rev. Sci. Instrum., 41, 1706,
1970.

Reed, R. D., E. G. Shelley, J. C. Bakke, T. C. Sanders, and J. D. McDaniel,
A low-energy channel-multiplier spectrometer for ATS-E, IEEE Trans.
Nucl. Sci., NS-16, 359, 1969.

Robbins, D. E., A. J. Hundhausen, and S. J. Bame, Helium in the solar
wind, J. Geophys. Res., 75, 1178, 1970.

Rosenbauer, H., G. Grünwaldt, M. D. Montgomery, G. Paschmann, and N. Schopke,
HEOS-2 plasma observations in the distant polar magnetosphere - the
plasma mantle, submitted for publication to J. Geophys. Res., 1975.

Sharp, R. D., R. G. Johnson, and E. G. Shelley, Satellite measurements of
auroral alpha particles, J. Geophys. Res., 79, 5167, 1974.

Shea, M. F., G. B. Shook, J. B. Reagan, L. F. Smith, and T. C. Sanders,
Channel-multiplier instrumentation for the measurement of low-energy
auroral particles, IEEE Trans. Nucl. Sci., NS-14, 96, 1967.

Shelley, E. G., and W. C. Feldman, Simultaneous He^{++} and H^+ observations in
the solar wind and the low-altitude dayside cusp (abstract), EOS Trans.
Am. Geophys. U., 56, 431, 1975.

Shelley, E. G., R. G. Johnson, and R. D. Sharp, Satellite observations of
energetic heavy ions during a geomagnetic storm, J. Geophys. Res., 77,
6104, 1972.

Shelley, E. G., R. G. Johnson, and R. D. Sharp, He^{++} and H^+ spectra in the
dayside cusp (abstract), EOS Trans. Am. Geophys. U., 54, 425, 1973.

Shelley, E. G., R. G. Johnson, and R. D. Sharp, Morphology of energetic O^+ in the magnetosphere, in Magnetospheric Physics, B. M. McCormac, ed., D. Reidel Publ. Co., Dordrecht-Holland, p. 135, 1974a.

Shelley, E. G., R. D. Sharp, and R. G. Johnson, Dayside convection electric field deduced from ion measurements in the low-altitude cusp (abstract) EOS Trans. Am. Geophys. U., 55, 1175, 1974b.

Vasyliunas, V. M., Summary of magnetospheric cleft symposium, Trans. Am. Geophys. U., 55, 60, 1974.

Whalen, B. A., and I. B. McDiarmid, Further low-energy auroral-ion composition measurements, J. Geophys. Res., 77, 1306, 1972.

Winningham, J. D., Characteristics of magnetosheath plasma observed at low altitude in the dayside magnetospheric cusps, in Earth's Magnetospheric Processes, B. M. McCormac, ed., D. Reidel Publ. Co., Dordrecht, Netherlands, p. 69, 1972.

Yasuhara, F., S.-I. Akasofu, J. D. Winningham, and W. J. Heikkila, Equatorward shift of the cleft during magnetospheric substorms as observed by Isis I, J. Geophys. Res., 78, 7286, 1973.

FIGURE CAPTIONS

Fig. 1. Electron and proton fluxes observed during a pass through the low-altitude dayside cusp region on 7 March 1972. The vertical dashed line at approximately 0531:18 UT is the "trapping boundary" for electrons with energies greater than 130 keV. The fourth panel from the bottom is the integral H^+ flux measured by the mass spectrometer. Note that these are log plots with each panel covering several decades in range. Universal time and invariant latitude are indicated along the horizontal axis.

Fig. 2 Example of mass spectrum from mass spectrometer. The ion flux is dispersed in mass over 64 channels. The solid curve shows composite least-squares fit to the data with H^+ and He^{++} . The dashed curves show the expected responses of the instrument to pure He^{++} and pure H^+ at the calculated strengths.

Fig. 3. Latitudinal distributions of the integral He^{++} and H^+ fluxes in the energy-per-unit-charge range between 0.74 keV and 12.1 keV. The trapping boundary from Figure 1 has been included for reference. Note that the scale is linear and the He^{++} flux has been multiplied by 10.

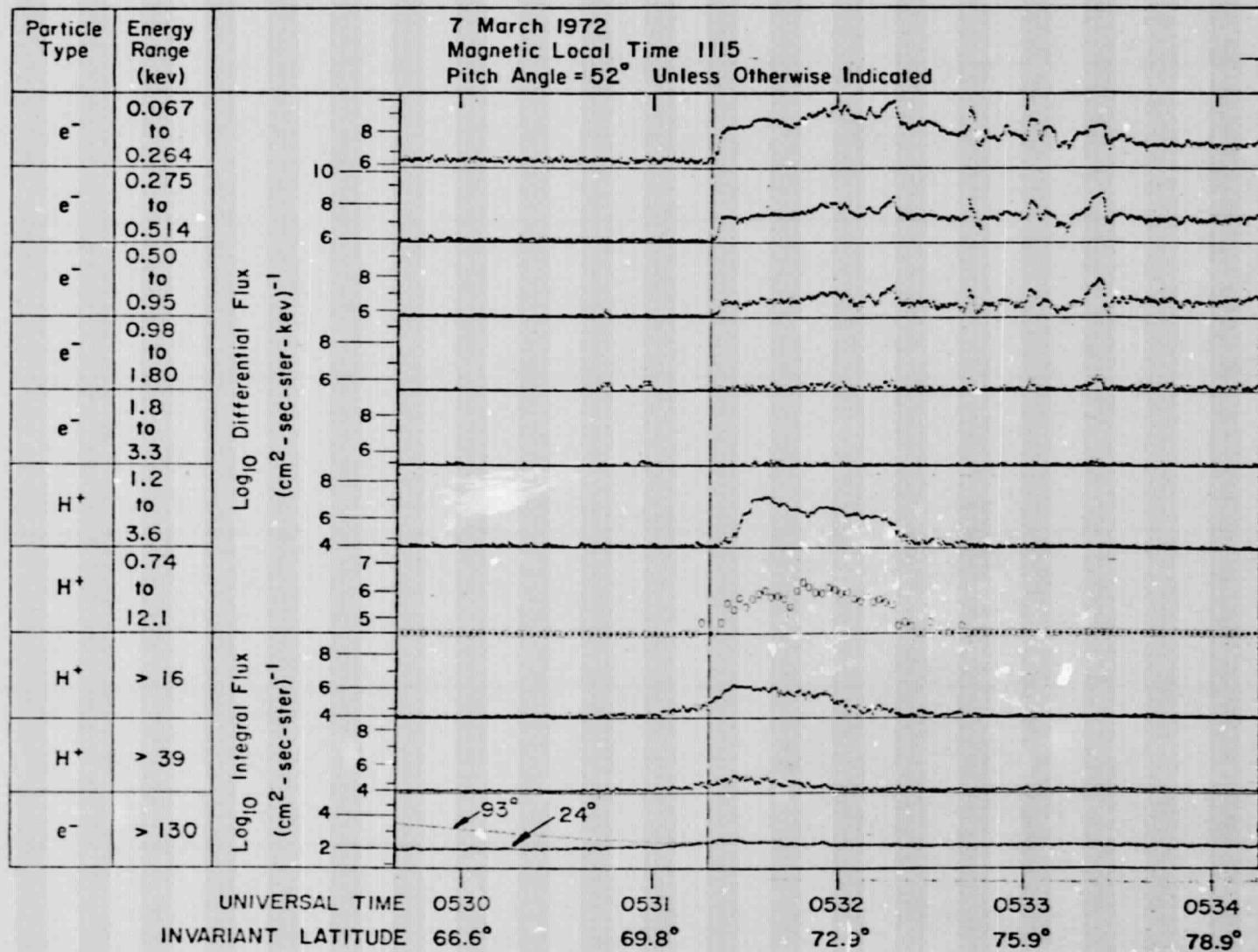
Fig. 4. Latitudinal distributions of individual velocity groups for He^{++} and H^+ . The same symbols have been used for ions of

Fig. 4. (cont'd) approximately the same energy per nucleon (velocity). Note the latitudinal displacement as a function of velocity for both ion species.

Fig. 5. Schematic representation of particle motions in the polar cusp showing the effects of anti-sunward convection on the particle trajectories. The solid circles represent relatively fast ions and the open circles represent slower ions [from Figure 12 of Rosenbauer et al., 1975]

Fig. 6. Location of low-latitude limits of individual particle velocity groups vs. their inverse velocities. The solid circles and open circles are from mass spectrometer measurements of H^+ and He^{++} , respectively. The horizontal bars represent the time resolution of the measurements. The symbol \square is the limit determined from the measurements with a permanent magnetic ion spectrometer which is sensitive primarily to H^+ . Symbols \otimes and \odot are limits determined from integral ion detectors with thresholds to protons at approximately 16 and 38 keV, respectively. The (e^-) symbol represents the low-latitude limit for electrons with energies between 70 eV and 260 eV. See text for definitions of low-latitude limits. The vertical dashed line is the approximate electron trapping boundary taken from Figure 1. The diagonal solid line corresponds to the expected dependence of the low-latitude limit on particle velocity for anti-sunward convection in the cusp.

Fig. 7. H^+ and He^{++} energy-per-nucleon spectra averaged over the entire cusp (0531:20 to 0532:34 UT--see Figure 3). This averaging reduces the absolute flux level for both ion species by approximately a factor of five. The error bars represent counting statistics only. The solid curves correspond to energy-per-nucleon spectra for convecting Maxwellian distributions in the direction of convection with the indicated speed and temperature parameters. The dashed lines joining the higher-energy points are intended to aid the eye only.



ORIGINAL PAGE IS
OF POOR QUALITY

FIGURE 1

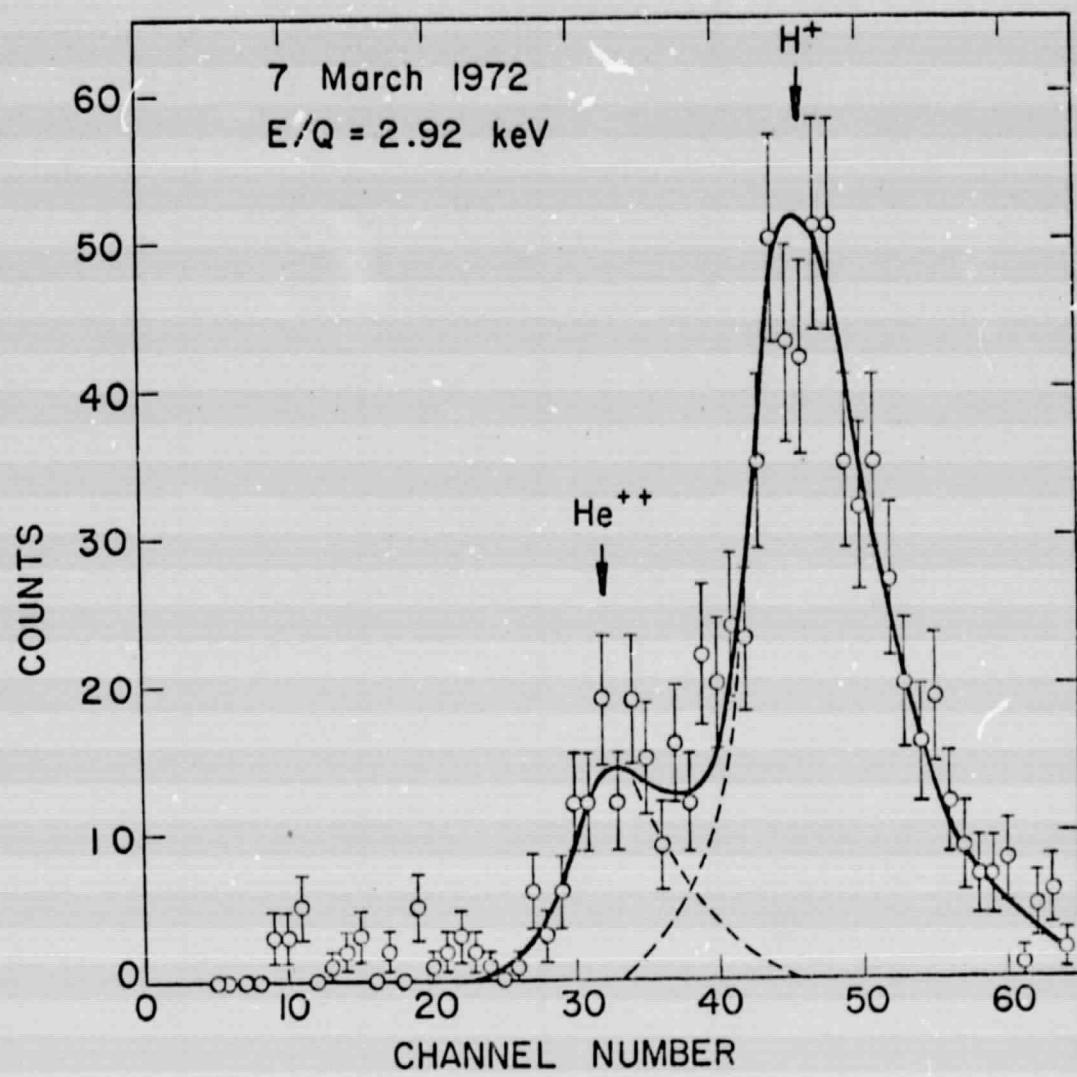


FIGURE 2

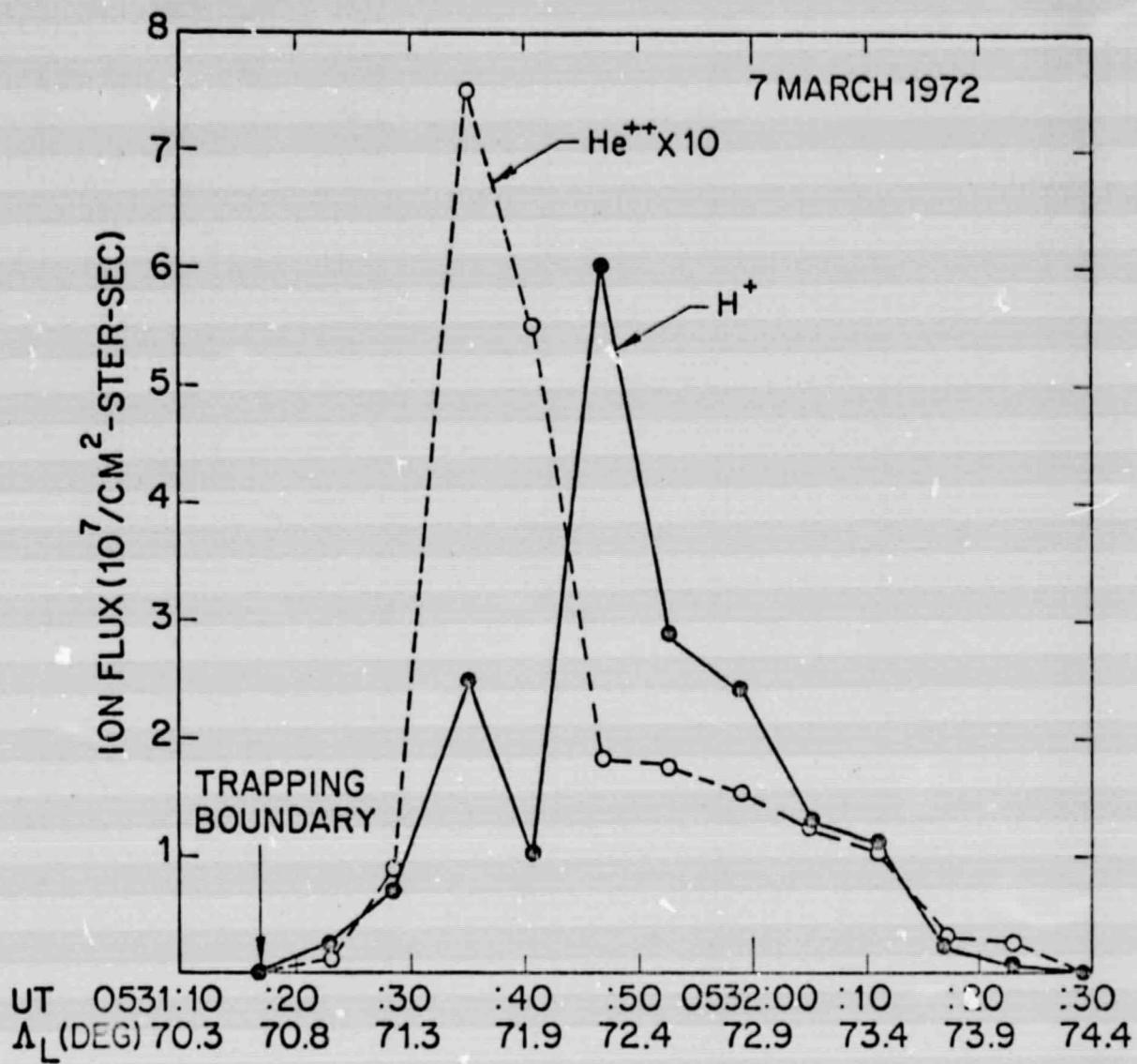


FIGURE 3

7 March 1972

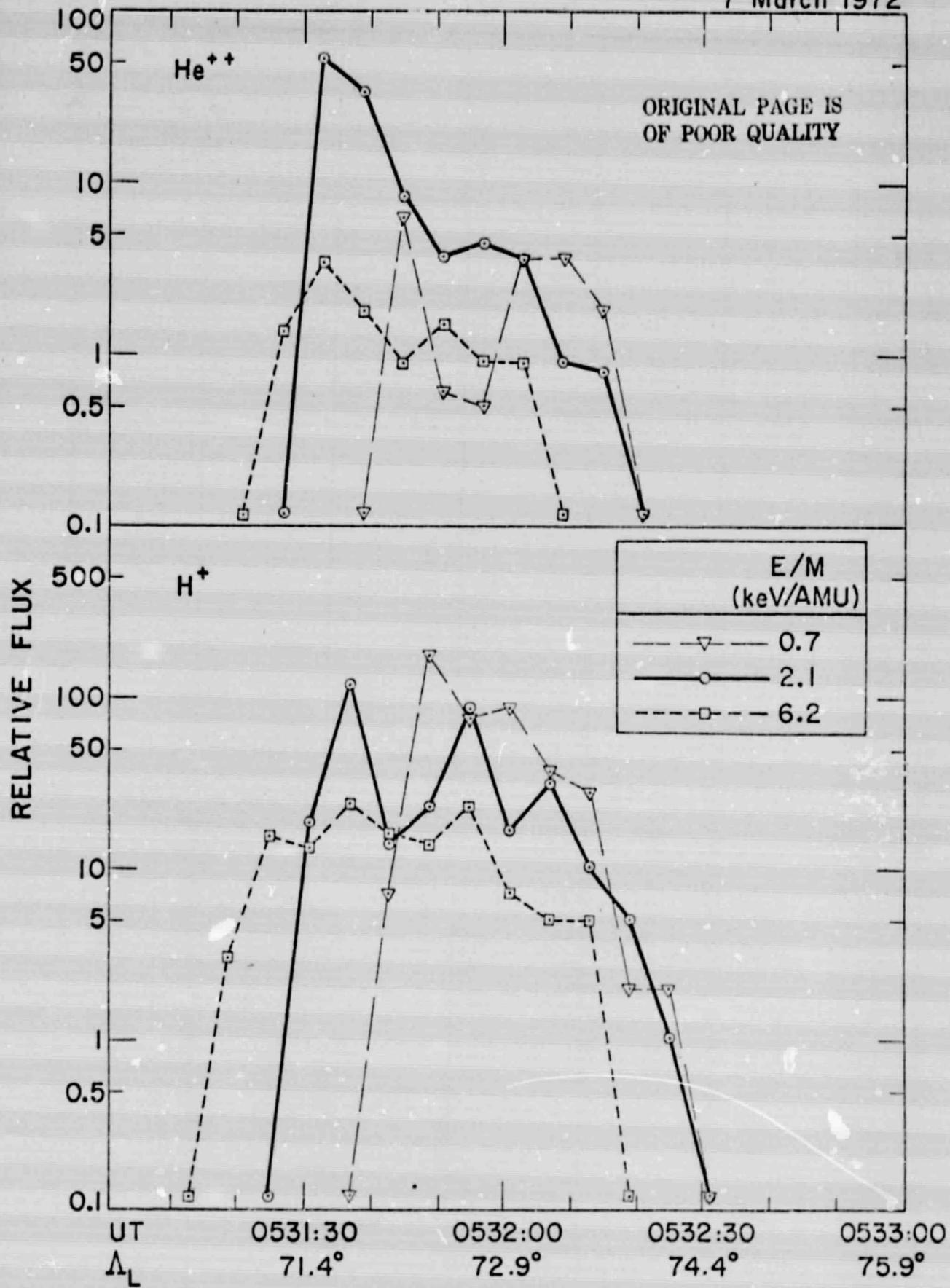


FIGURE 4

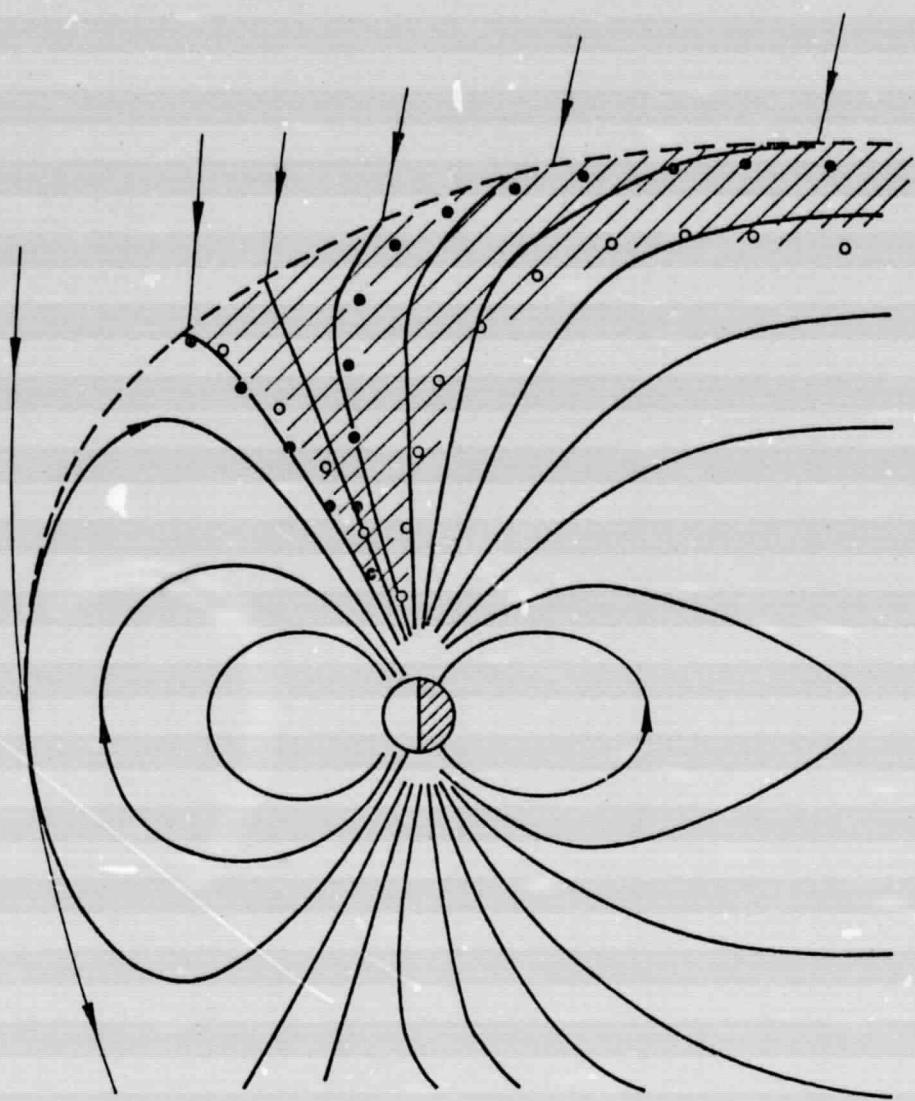


FIGURE 5

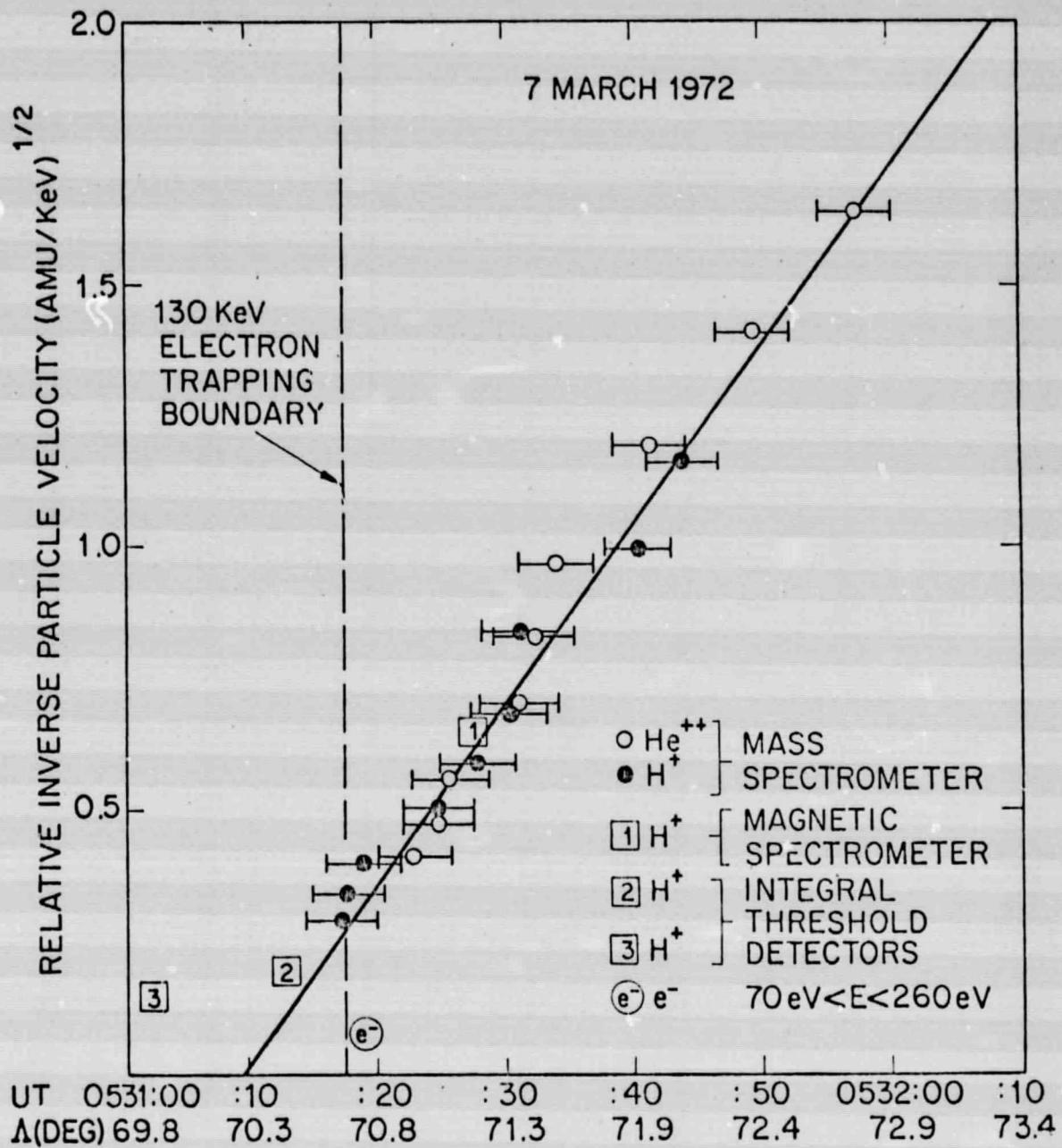


FIGURE 6

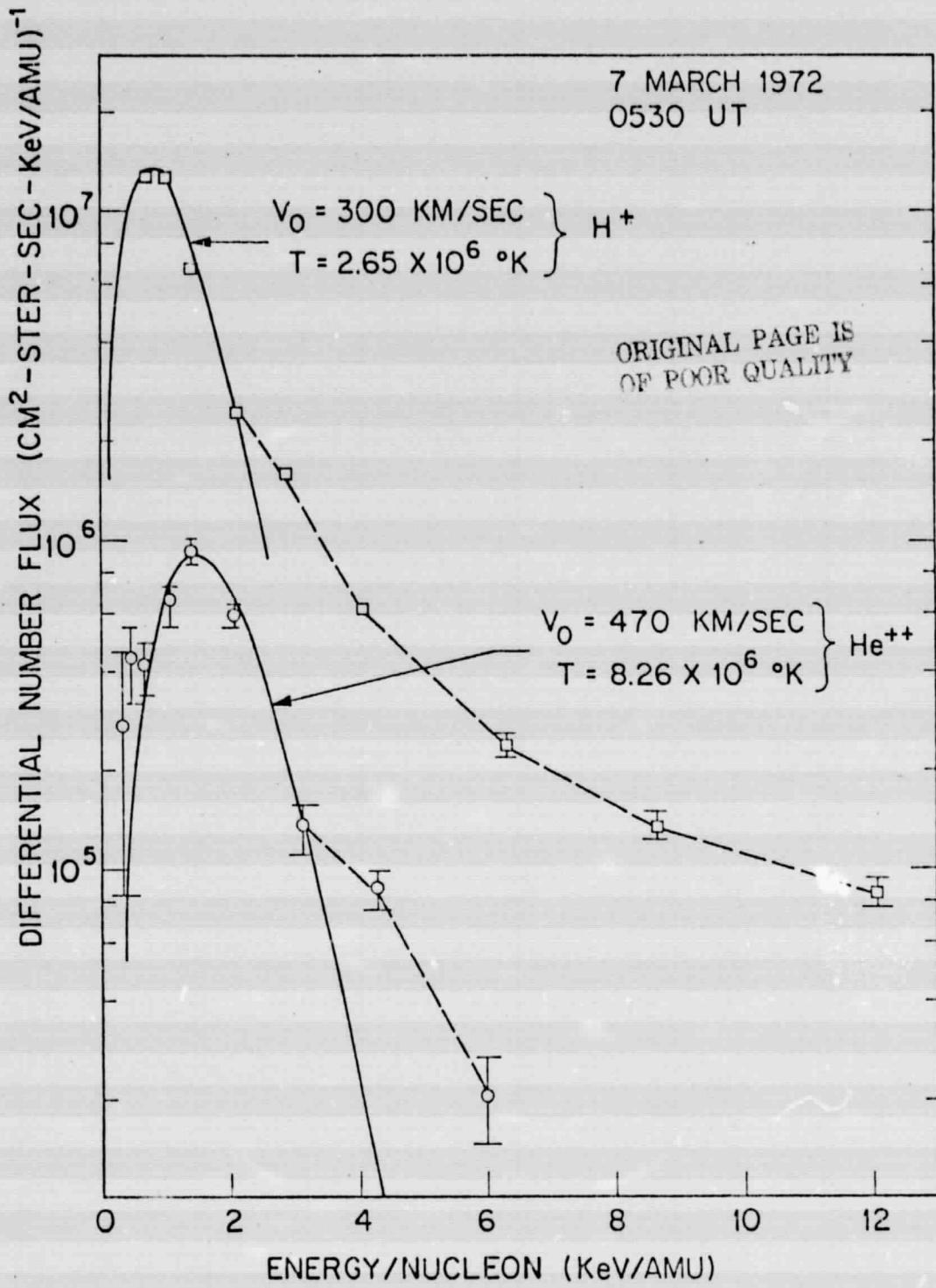


FIGURE 7